Journal of Electromyography and Kinesiology 47 (2019) 88–95

Contents lists available at ScienceDirect

Journal of Electromyography and Kinesiology

journal homepage: www.elsevier.com/locate/jelekin

Ratings of perceived fatigue predict fatigue induced declines in muscle strength during tasks with different distributions of effort and recovery

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ARTICLE INFO

Keywords:
Rating of perceived fatigue
Muscle fatigue
Maximal voluntary contraction strength
Force time-history

ABSTRACT

The purpose of this study was to quantify the relationship between ratings of perceived fatigue (RPF), using a modified Borg CR-10 scale, and muscle fatigue accumulation, as defined by maximal voluntary contraction strength (MVC) declines, during two complex MVC-relative tasks (conditions) that cause muscle fatigue and allow recovery. Nine female participants completed the fatiguing tasks, composed of a series of submaximal, isometric efforts (task plateaus) requiring isometric flexion at the distal interphalangeal joint of the thumb. Significant partial correlations between RPF and MVC, while controlling for task plateau intensity (%MVC), were found in 6/9 participants. A significant linear regression model, explaining 86.2% of the variance in mean MVC decline, was obtained with 3 predictor variables: mean RPF ($p < 0.001$), Task Plateau ($p < 0.001$), and the interaction between mean RPF and Task Plateau (RPF × Task Plateau; $p = 0.014$). The observed linear relationship between RPF and MVC declines, both at the participant and group level support, the use of RPF to estimate the instantaneous fatigue status of the muscle in tasks that allow both muscle fatigue and recovery.

1. Introduction

Subjective ratings of perceived exertion (RPE) or discomfort (RPD) are simple, and indirect scales of muscle fatigue accumulation during activities performed in the workplace, rehabilitation or sports settings. RPE values are obtained using the Borg CR-10 scale and RPD values are obtained using a modified version of the Borg CR-10 scale (Borg, 1990). Several authors have demonstrated moderate to strong relationships between perceived ratings (exertion, discomfort) and objective measures of muscle fatigue such as endurance time or myoelectric indicators (Frey Law et al., 2010; Iridiastadi and Nussbaum, 2006; Rashedi and Nussbaum, 2016; Rose et al., 2014; Troiano et al., 2008). In contrast to objective measures of muscle fatigue (i.e. decline in strength, changes in electromyography) subjective ratings of exertion or discomfort, provide an inexpensive, simple, and non-invasive estimate of muscle fatigue accumulation.

Despite moderate to strong correlations between RPE and RPD with objective measurements of muscle fatigue, these measures are not necessarily specific to fatigue sensations. Typically, RPD provides a global indicator of an individuals' changes in perceived exertion, fatigue and pain (Frey Law et al., 2010). Although pain often accompanies muscle fatigue accumulation, pain perception is highly variable between individuals and, therefore, may result in increased variability in RPD that is not necessarily related to the level of accumulated muscle fatigue (Fillingim, 2005; Frey Law and Avin, 2010). RPE relates to the perceived challenge of an activity and can have limited sensitivity to muscle fatigue accumulation in low intensity efforts or rest. In fact, Micklewright et al., (2017) found that during rest periods following a fatiguing task, RPE dropped to zero, while physiological indicators of muscle fatigue (increased blood lactate concentration, increased respiratory exchange ratio (VCO_2/VO_2) were still elevated, as compared to baseline (pre-task) values. Although changes in both RPD and RPE are related to muscle fatigue accumulation, these metrics may not provide a direct indicator of muscle fatigue accumulation across individuals and varied effort intensities.

During fatiguing tasks, the relationship between muscle fatigue and ratings of perceived fatigue, instead of either exertion or discomfort, has not been studied extensively. Recently, Micklewright et al. (2017) performed a series of experiments to develop and validate a rating of perceived fatigue (RPF scale that was a modified version of the Borg CR 10 scale with individuals indicating values ranging from 0 (not fatigued at all) to 10 (total fatigue & exhaustion – nothing left). During a graded cycling test in which workload was incrementally increased by 25 W every 100 s until exhaustion, RPF exhibited strong correlations with systemic, physiological indicators of muscle fatigue (blood lactate concentration, oxygen uptake, carbon dioxide production, respiratory

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https://doi.org/10.1016/j.jelekin.2019.05.012
Received 12 January 2019; Received in revised form 18 April 2019; Accepted 17 May 2019
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exchange ratio). In the recovery period following the cycling task, RPF continued to exhibit strong correlations with these systemic, physiological indicators of muscle fatigue where as RPE did not, as it dropped immediately to baseline because individuals were at rest. A limitation of this work is that it did not explore the relationship between RPF and a local, muscle or muscle group specific, measure of muscle fatigue, such as a decline in maximal voluntary contraction strength (MVC). Muscle fatigue is the temporary decrease in MVC throughout, or following, prolonged or repeated efforts and encompasses both central and peripheral contributions (Vøllestad et al., 1997). Nonetheless, Micklewright et al. (2017) was one of the first to show convergent validity between RPF data and objective, albeit systemic, measures of muscle fatigue, highlighting the potential viability of this subjective indicator of muscle fatigue.

For the multi-disciplinary use of the RPF scale as a subjective indicator of muscle fatigue, its performance needs to be established for a variety of tasks with different demands. Micklewright et al. (2017) studied a task with progressively increasing intensity efforts that did not allow fatigue recovery during the task. Research on muscle fatigue accumulation in MVC-relative tasks, comprised of task cycles with isometric exertions of different intensities, have revealed a 'force-time history effect'. Thus, instantaneous fatigue accumulation during a task depends on the current status of the muscle and the immediately preceding exertions (Potvin and Fuglevand, 2017; Sonne et al., 2015; Sonne and Potvin, 2015). Therefore, fatigue recovery is not exclusive to periods of complete rest and can occur during submaximal exertions that follow higher intensity exertions (Sonne et al., 2015). To be used as an indicator of instantaneous levels of muscle fatigue in workplace or performance settings, the strength of the relationship between RPF and objective measures of instantaneous muscle fatigue needs to be demonstrated during tasks that allow fatigue recovery either by intermittent periods of rest and/or different intensity submaximal efforts.

The global purpose of this study is to investigate the relationship between RPF and MVC declines with muscle fatigue accumulation, during two complex MVC-relative tasks that allow recovery. The two tasks studied (conditions) contained the same sequence of various submaximal isometric exertions within task cycles but differed by the distribution of rest within the task cycle. Thus, the secondary purpose of the study is to explore any potential force-time history effects on the RPF-MVC relationship by comparing this relationship across two conditions, with the same sequence of effort levels but different allocations of rest within a task cycle (i.e. evenly spaced and front loaded).

2. Methods

2.1. Participants

Nine right-handed females (21.3 + / − 1.16 years), free of any upper limb musculoskeletal disorders during the past year, participated in the study. Female participants were selected in this study with a potential ergonomic application in mind. As in other ergonomics research, females were chosen as the participants because most occupational task demand limits are set based on the 25th percentile (ie. "weak") female (La Delfa et al., 2014; Sonne et al., 2015; Sonne and Potvin, 2015). The university's research ethics board approved the study and each participant provided informed consent.

2.2. Instrumentation and data acquisition

Our study consisted of two fatiguing tasks (conditions) composed of a series of submaximal, isometric efforts (task-plateaus) requiring isometric flexion at the distal interphalangeal (DIP) joint of the thumb. The flexor pollicis longus (FPL) is the only muscle that contributes to flexion at the DIP joint and, therefore, the MVC produced in DIP flexion directly reflects fatigue accumulation of FPL, as there are no synergist muscles to contribute force with the onset of fatigue (Enoka and

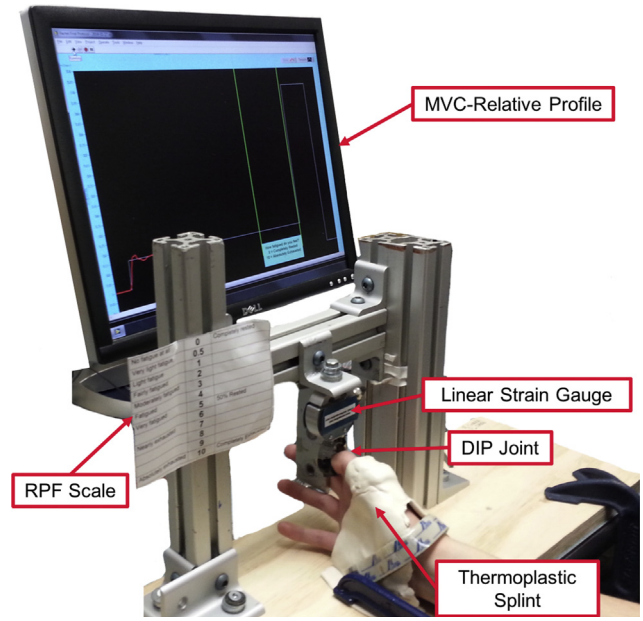

Fig. 1. The apparatus used to restrict movement to the DIP joint of the thumb throughout the fatigue protocols (conditions). The subject is wearing a custom fitted thermoplastic brace that is clamped into a position, allowing their thumb to rest in a metal ring attached to a linear strain gauge. A metal bar kept the subject's remaining digits extended when they exerted force in flexion against the metal ring.

Rating of Perceived Fatigue (RPF) Scale		
Completely Rested	0	No fatigue at all
	0.5	Very light fatigue
	1	Light fatigue
	2	Fairly fatigued
	3	Moderately fatigued
	4	Fatigued
50% Rested	5	Very fatigued
	6	
	7	Nearly exhausted
	8	
	9	
Completely Fatigued	10	Absolutely exhausted

Fig. 2. The rating of perceived fatigue (RPF) scale used in this study. The left column includes descriptors of the recovery process, whereas the right side includes descriptors of the fatigue process. The scale was located within subject's line of sight, to the right of the computer monitor, while they completed the fatigue protocols. Participants used this scale to rate their perceived fatigue once every 16 s.

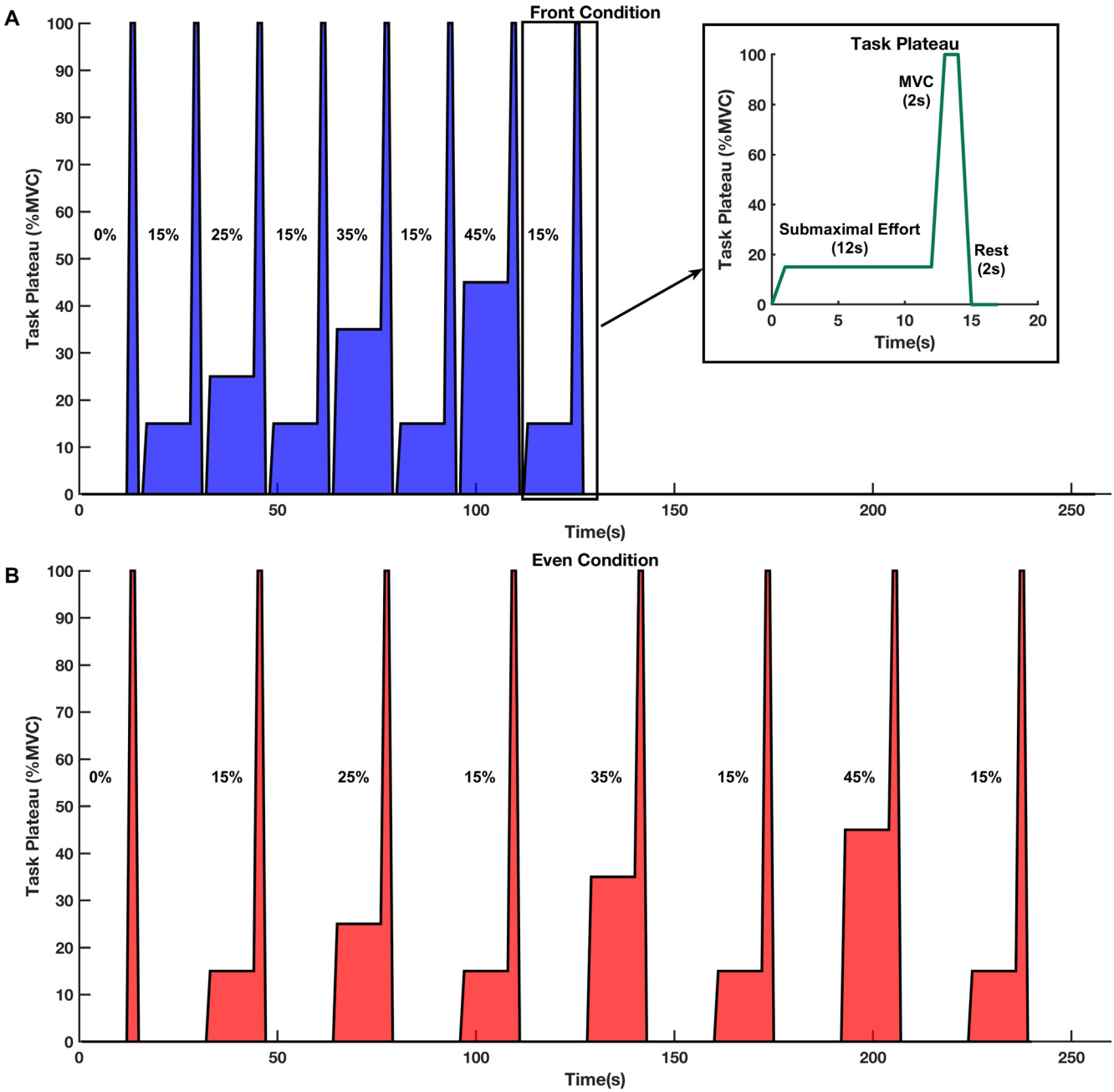

Fig. 3. Force time-histories of one cycle of the repetitive task for the (A) Front and (B) Even conditions. Participants were shown this template on screen, and their generated force level was overlaid on top in real-time, so they could match their effort with that required. Both conditions had the same sequence of submaximal task plateaus but differed in the arrangement of rest within the task cycle. A task plateau, seen in the top right of (A) consisted of a 12 s submaximal effort followed by an MVC and 2 s of rest. Participants provided RPF ratings during the last 2 s of the submaximal effort, immediately prior to the MVC exertion. Participants completed 5 cycles in both conditions.

Duchateau, 2008).

An s-type strain gauge (445 N max, Omegadyne Inc., Laval, QC, Canada), mounted on a slotted rail frame (80/20 Inc., Columbia City, IN), measured the force created when participants produced a flexion moment at the DIP joint of the thumb (Fig. 1). Participants sat in front of a computer screen in an adjustable office chair with their forearm on the armrest aligned with the strain gauge (elbow angle of 90°). We adjusted the position of the strain gauge so that the participants' thumb rested comfortably on the attached padded metal ring.

Participants came to the lab on 3 separate occasions, separated by at least 48 h. During the first session, we fitted participants with a custom thermoplastic brace used to isolate the moment about the DIP joint. Participants then completed a practice protocol to familiarize them with: (1) wearing a brace and being secured into position, (2) giving maximal and sustained isometric contractions of the thumb's DIP joint when prompted on screen, and (3) providing ratings of perceived fatigue using the RPF scale (Fig. 2). In randomized order, participants completed one of two fatigue protocols during the second and third visits.

At the start of each session, we used the weight of the participant's thumb resting on the metal ring to zero the strain gauge, as this represents 0% of their MVC. Participants then completed a maximum isometric effort (2 s in duration) of DIP joint flexion which was inputted it into custom LabView software (National Instruments, Austin, TX) to scale the force required at each task-plateau to a percentage of their rested MVC. We sampled the amplified (1000 ×) force data at 2000 Hz

Table 1
The correlation coefficients between RPF and MVC decline (subscripted as MVC RPF) and the partial correlation coefficients between RPF and MVC after adjusting for Task Plateau (subscripted as MVC RPF · Task Plateau for each participant (total = 9) during each condition (Front, Even). An asterisk (*) denotes the significant ($p < 0.05$) correlations or partial correlations.

Participant	Even		Front	
	$r_{MVC\ RPF}$	$r_{MVC\ RPF.\ Task\ Plateau}$	$r_{MVC\ RPF}$	$r_{MVC\ RPF.\ Task\ Plateau}$
1	0.56*	0.71*	0.58*	0.65*
2	0.19	0.45*	0.14	0.22
3	−0.15	0.55*	0.05	0.21
4	0.85*	0.84*	0.81*	0.76*
5	0.23	0.29	0.67*	0.61*
6	0.50*	0.50*	0.52*	0.48*
7	0.74*	0.65*	0.78*	0.71*
8	0.44*	0.50*	0.75*	0.69*
9	0.38*	0.56*	0.80*	0.81*
Mean	0.41	0.56	0.57	0.57
Standard Dev.	0.30	0.16	0.28	0.22
n	9	9	9	9

and converted it to a digital signal using a12-bit A/D card (National Instruments, Austin, TX). Force data were normalized to maximum (% MVC) in real-time and displayed for participants on a computer screen alongside a pre-programmed force template so they could match their effort to that required. To encourage maximal effort, when prompted to perform MVCs during the task participants were shown their baseline MVC value (100%) and asked to try to match this force level.

2.3. Rating of perceived fatigue (RPF) scale

We developed an RPF scale by modifying the Borg CR-10 scale used to provide an indicator of perceived exertion (Borg, 1990). At the time of data collection, the RPF scale developed by Micklewright et al. (2017) was not published so we designed the descriptors associated with the numeric values in the RPF scale, but they do have similarities with the scale of Micklewright et al. (2017). Instead of diagrammatic components included in the RPF scale by Micklewright et al. (2017), descriptors of fatigue recovery were included. We decided to add this component to the scale because the tasks performed by participants included periods of rest and subsequent fatigue recovery, with the intention that these descriptors could help participants to conceptualize a fluctuation in fatigue accumulation due to recovery. Although we acknowledge the established exponential relationship between the perceived intensity of sensations (i.e. pain) and physical stimuli (Borg, 1990; Stevens and Mack, 1959) perceived fatigue (or recovery) requires integration of physical (pain, exertion) and cognitive (effort, motivation) elements associated with the stimuli (Micklewright et al., 2017). Therefore, as one of the first RPF scales to include descriptors of fatigue recovery, we decided to use a simple, linear approach by anchoring 50% recovery at the 5/10 point on the scale.

2.4. Complex MVC-relative profiles

Each condition consisted of 5 cycles, of 8 task plateaus of flexion at the DIP joint of the thumb. Each task plateau required a 12 s submaximal, isometric effort, followed by a 2 s MVC and 2 s of rest (Fig. 3). In both conditions, task plateaus were in the following sequence for each cycle: 0-15-25-15-35-15-45-15 (%MVC). However, the conditions had different loading patterns. The 'Front' condition consisted of consecutive task plateaus followed by 140 s of rest, giving a total cycle time of 256 s and a duty cycle of 38.7%. The 'Even' condition had 16 s of rest distributed evenly between task plateaus in the cycle, giving a giving a total cycle time of 240 s and a duty cycle of 41.3% (Fig. 3). Overall, during each condition, participants completed MVCs following each of the 40 task plateaus (5 cycles × 8 task plateaus/cycle) and a final MVC after completion of the 5th cycle, resulting in a total of 41 MVCs.

2.5. Data analysis

The raw force data were smoothed using a 0.5 s moving average, normalized to the rested MVC (volts), and subtracted from 100% to determine the decline in strength (%MVC) following each task plateau.

2.6. Statistical analysis

2.6.1. Participant level

Correlation analyses on each participants' data were performed separately for the two conditions (front, even). In each experimental condition, we recorded 41 MVCs and RPFs. Pearson product moment correlations between MVC and RPF ($r_{RPF\ MVC}$), MVC and Task Plateau ($r_{MVC\ Task\ Plateau}$), and RPF and Task Plateau ($r_{RPF\ Task\ Plateau}$) were calculated using the data from each participant for both conditions. A partial correlation between MVC and RPF, while controlling for Task Plateau ($r_{MVC\ RPF\cdot\ Task\ Plateau}$), was also calculated using Eq. (1).

$$r_{MVC\ \ RPF\ \cdot Task\ \ Plateau} = \frac{(r_{MVC\ \ RPF} - r_{MVC\ \ Task\ \ Plateau} \times r_{RPF\ \ Task\ \ Plateau})}{\sqrt{(1 - r^2_{MVC\ \ Task\ \ Plateau})} \times (1 - r^2_{RPF\ \ Task\ \ Plateau})} \quad (1)$$

A total of 27 correlations (9 participants × 2 conditions × 3 correlations) and 18 partial correlations (9 participants × 2 conditions) were computed. The $r_{RPF\ MVC}$ and $r_{MVC\ RPF.\ Task\ Plateau}$ values, from each participant and both conditions, were transformed using a Fisher's z transformation and inputted into a single sample t-tests ($p < 0.05$) to determine whether the mean correlation between MVC and RPF or partial correlation between MVC and RPF, while controlling for Task Plateau, was significantly different from zero (Micklewright et al., 2017).

2.6.2. Group level

For each condition and task plateau level (n = 82) the mean RPF and MVC data, across participants, were computed. A stepwise linear regression model (p to enter < 0.05, p to remove < 0.1) was then developed using these data to test if RPF, Condition, Task Plateau, and/or the interactions between these variables could predict mean MVC levels as they decline with fatigue. Condition (Front or Even) was treated as a categorical variable in the model.

3. Results

3.1. Participant level

Significant correlations and partial correlations (when controlling for Task Plateau) existed between MVC and RPF for both conditions in 6/9 participants (Table 1; Fig. 4). The average partial correlation between RPF and MVC, while controlling for Task Plateau, in the Even ($\mathbf{r}_{\mathbf{RPF\ MVC.\ Task\ Plateau}} = 0.56$) and Front ($\mathbf{r}_{\mathbf{RPF\ MVC.\ Task\ Plateau}} = 0.57$) conditions were significantly different from zero (Even tstat(8) = 4.32, p = 0.002; Front tstat(8) = 8.44p < 0.001). There was no significant difference in the $\mathbf{r}_{\mathbf{RPF\ MVC.\ Task\ Plateau}}$ between conditions (tstat (8) = 0.017p = 0.9868).

The average correlation between MVC and RPF across participants in both the Front ($\mathbf{r}_{\mathbf{RPF\ MVC}} = 0.57$) and Even ($\mathbf{r}_{\mathbf{RPF\ MVC}} = 0.42$) conditions were significantly different from zero (Even tstat (8) = 12.56, p < 0.001; Front tstat(8) = 6.2485p < 0.001).

In the Even condition, controlling for Task Plateau improved the average correlation coefficient between RPF and MVC, ($\mathbf{r}_{\mathbf{RPF\ MVC.\ Task\ Plateau}} = 0.56 > \mathbf{r}_{\mathbf{RPF\ MVC}} = 0.42$). However, the average correlation coefficient between RPF and MVC did not improve when controlling for Task Plateau in the Front condition ($\mathbf{r}_{\mathbf{RPF\ MVC.\ Task\ Plateau}} = 0.57$ vs. $\mathbf{r}$

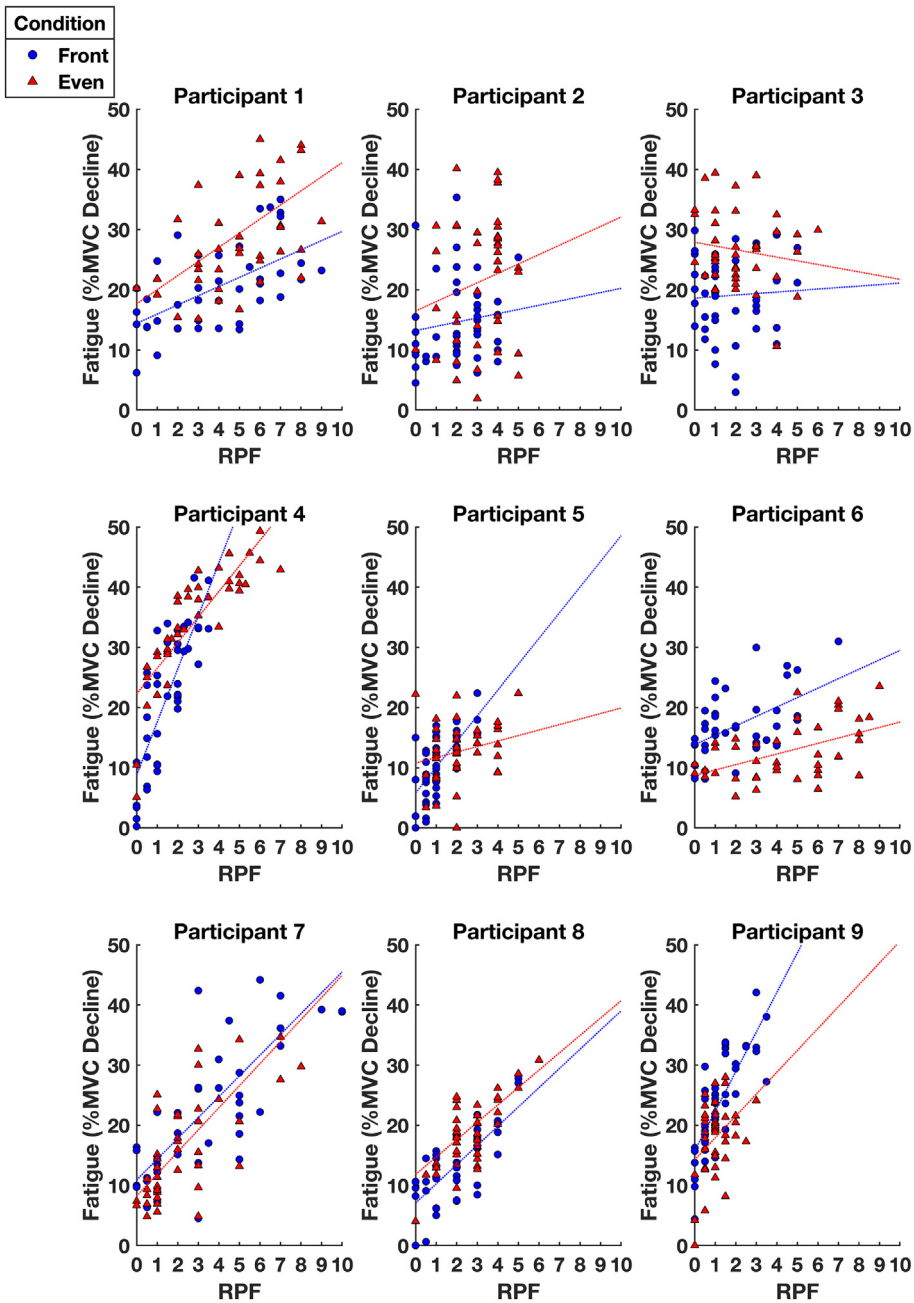

Fig. 4. RPF plotted against fatigue (% MVC Decline) during each of the two conditions, shown for each of the 9 participants. The least squares line of best fit for each condition is also shown (dashed line) in the same colour as the corresponding data points.

Table 2
The coefficients and associated standard errors for each predictor term included in the linear regression model of the MVC decline. A stepwise procedure (p to enter < 0.05, p to remove < 0.1) was used to select the predictor terms.

Predictor Variable	Regression Coefficient ± Standard Error
Intercept	11.53 ± 0.77
Task Plateau	−0.11 ± 0.04
Mean RPF	4.90 ± 0.31
Mean RPF × Task Plateau	−0.03 ± 0.01

$_{\text{RPF MVC}}$ = 0.57).

3.2. Group level

A significant linear regression model, explaining 86.2% of the variance in mean MVC decline, was obtained with the following 3 predictor variables: mean RPF ($p < 0.001$), Task Plateau ($p < 0.001$), and the interaction between mean RPF and Task Plateau (RPF × Task Plateau; $p = 0.014$) (Table 2, Fig. 5 and Fig. 6). The first variable entered in the stepwise process was RPF and it explained 70.3% of the variance. The next variable was Task Plateau, and it added an additional 14.4% and the third interaction variable added only 1.1%.

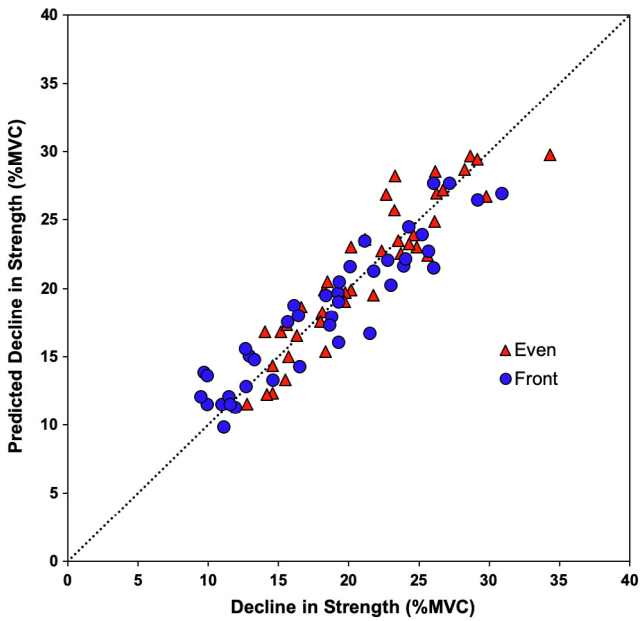

Fig. 5. The average and predicted decline in strength during Front and Even conditions (n = 41 for each). The predicted values are obtained from the regression equation including average RPF and Task Plateau and their interaction term (r^2 = 0.862).

4. Discussion

This study was one of the first to characterize the relationship between MVC declines and subjective ratings of muscle fatigue during two complex tasks with isometric exertions at various relative intensities, and with different rest distributions. For the majority of participants, there was a significant linear correlation between RPF and MVC decline during both conditions, especially when controlling for the intensity of the preceding exertion (Task Plateau). Second, at the group level, the mean MVC decline in either condition could be predicted with the mean RPF and task plateau level, as well as their interaction term. Inclusion of the intensity of the preceding exertion (%MVC), as a predictor of MVC decline in the linear model, may indicate a force-time history effect. Overall, our data supports RPF as a subjective measure of muscle fatigue, showing a linear relationship with MVC decline in repetitive, fatiguing tasks.

The subjective RPF scale was linearly related to objectively measured levels of muscle fatigue accumulation, during tasks that incorporate intermittent periods of rest. Micklewright et al. (2017), also showed that RPF exhibited linear correlations with objective measures of muscle fatigue (blood lactate concentration, oxygen uptake, carbon dioxide production) during periods of increasing exertion and a subsequent period of complete rest. In the tasks performed in this study, evident in the MVC declines, muscle fatigue accumulation was not continually increasing over the course of each trial, as there was recovery occurring between cycles in the Front condition.

Although linear relationships between subjective ratings of physical discomfort, pain or exertion using the Borg CR-10 scale and fatigue accumulation have been reported in tasks with isometric exertions and rest periods (Frey Law and Avin, 2010; Iridiastadi et al., 2008; Iridiastadi and Nussbaum, 2006; Rose et al., 2014), the present study was, to the best of our knowledge, the first to show that RPF exhibits a linear relationship with fatigue accumulation, as defined by force decline, in tasks eliciting both fatigue accumulation and recovery. The observed linear relationship between the subject RPF measure and MVC decline both at the participant and group level, indicate the potential usefulness of RPF as an estimate of the instantaneous fatigue status of the muscle in tasks that allow both muscle fatigue and recovery.

Task parameters such as contraction level, duty cycle or cycle time result in different rates of change in subjective and objective measures of muscle fatigue with respect to time. Increasing the duty cycle or cycle time of a task in combination or independent of one another, results in increased rate of muscle fatigue development and, therefore, rate of change in subjective and objective measures with respect to time (Iridiastadi and Nussbaum, 2006; Rashedi and Nussbaum, 2016). However, there is no indication of whether these task parameters influence the relationship between subjective and objective indicators of muscle fatigue. The MVC-relative tasks studied in this experiment consisted of varying contraction levels, and slight differences in duty cycle (38.7%for Front vs 41.3% for Even) and cycle time (256 s for Front and 240 s for Even) between the conditions.

Nonetheless, by accounting for the intensity of the immediately preceding effort, it was possible to use the same linear model to obtain a good estimate (RMSE = 2.18% MVC) of the mean instantaneous muscle fatigue accumulation based on RPF data for both conditions. It is also interesting that a linear relationship between RPF and MVC decline was established in both complex MVC-relative tasks studied (conditions), despite substantial differences in the placement of rest period(s) within the task cycle. At the group level, the stepwise linear regression model did not include the condition term, indicating that the placement of rest within the task cycles was not necessary to predict MVC decline. The RPF and Task Plateau variables captured within cycle differences between conditions in fatigue accumulation that may have resulted from differences in rest placement. In summary, differences in duty cycle and cycle time between the conditions were small making it difficult to infer as to whether duty cycle and cycle time influence the relationship between RPF and MVC decline. However, in tasks with the same sequence of submaximal efforts, similar mean force (Front: 7.7% MVC, Even: 8.3% MVC) and duty cycles (Front: 41.3% MVC, Even: 38.7% MVC) the placement of rest within a task cycle does not need to be considered to predict MVC decline if RPF and Task Plateau data are obtained.

It was interesting that the linear relationship between RPF and MVC decline improved when the intensity of the preceding exertion (Task Plateau) was included in the model. In a previous study of MVC-relative tasks consisting of different intensity submaximal handgrip exertions, Sonne et al. (2015) showed that the level of instantaneous muscle fatigue was dependent on the current fatigue state of the muscle as well as the intensity of the immediately preceding exertion. Increased muscle fatigue was observed after a 15% MVC contraction when performed after a rest period, whereas recovery was observed after this same intensity exertion when preformed after a 25% MVC effort; this phenomenon was termed the force-time history effect. In a follow up study, participants completed 4 MVC-relative tasks with the same duty cycle and set of task plateaus, yet different temporal arrangement (order) of the task plateaus (Sonne and Potvin, 2015). The order of task plateaus influenced fatigue accumulation during the first cycle of the task but not the final fatigue accumulation at the end of 5 cycles. The authors suggested that the force-time history effect, observed during the first task cycle, was due to post activation potentiation and thus dissipates as the task continues and fatigue accumulation increases. In the current study, the inclusion of task plateau intensity with RPF in the linear model, to predict MVC decline, instead suggests a force-time history effect on muscle fatigue perception. The negative regression coefficients for the Task Plateau (−0.11) and Task Plateau × RPF (−0.03) suggests that the intensity of the preceding exertion amplifies an individual's perception of fatigue. Individuals tend to over predict MVC using RPF, with a larger overprediction of fatigue following higher intensity exertions, hence a force-time history effect on RPF. Overall, to use the relationship between RPF as an indicator of MVC decline in applied fields, such as performance training or ergonomics, it would be beneficial to ask individuals to provide RPF after the same task within a cycle of the activity, or at the end of a cyclical event.

The linear relationship between RPF and MVC decline varied between individuals and was stronger when the participant mean data

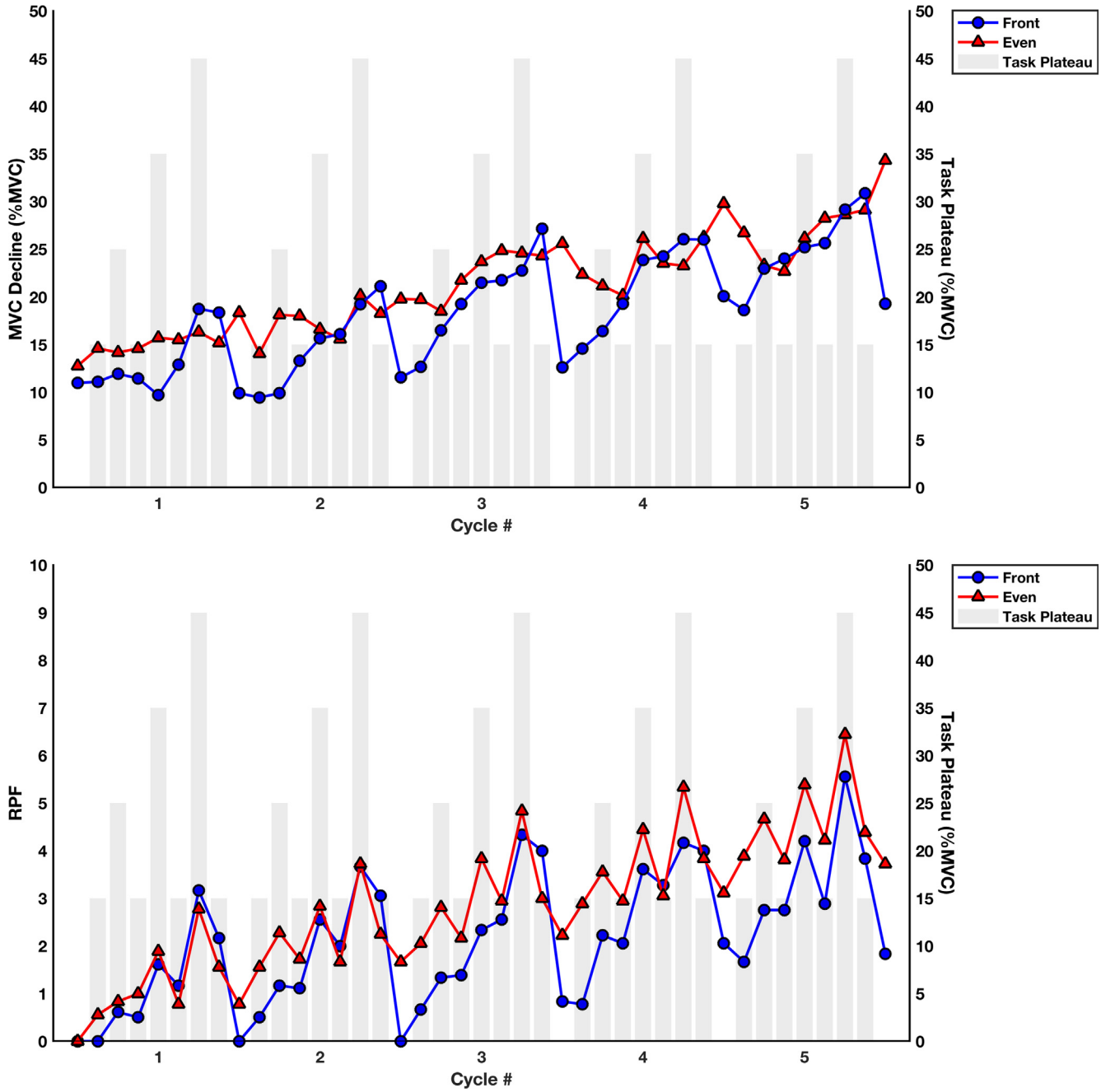

Fig. 6. (Top) Mean MVC decline in the front and even conditions shown for each task plateau completed throughout the 5 cycle task. (Bottom) Mean RPF in the front and even conditions shown for each task plateau completed throughout the 5 cycle task.

was considered. Variation in the relationship between subjective and object measures of muscle fatigue among individuals have been reported for other subjective ratings related to muscle fatigue (i.e. RPD) (Frey Law et al., 2010). Large differences in pain perception exist between individuals (Fillingim, 2005) and the same is likely true with regards to individuals' perception of the fatigue sensations. Although high inter-individual variability in the relationship between RPF and MVC declines highlights a potential limitation of the RPF scale, some of this variation may result because participants did not perform a 'calibration' procedure. It may be necessary to first 'calibrate' individuals to a "maximal" (or near maximal) fatigue level before using the RPF scale to quantify "submaximal" fatigue responses (Strimpakos et al., 2005).

Some limitations and assumptions from the study should be addressed. First, the task performed in this study was isolated to flexion at the DIP joint of the thumb allowing direct quantification of the MVC-decline of a single muscle (FPL). The relationship between RPF and MVC decline at joints where multiple muscles (synergists) contribute to joint moments needs to be quantified. Second, the participant population for this research consisted of university age females, but this relationship needs to be established with both males and female participants of varying ages. Age related differences in muscle fatigue accumulation rates exist (Hunter et al., 2005; Qin et al., 2014), yet it is unclear whether an individuals' perception of fatigue also differs with age. Overall, the relationship between RPF and MVC decline should be studied within different populations of individuals performing tasks that cause muscle fatigue accumulation at joints with muscle synergists.

5. Conclusion

A linear relationship between RPF and MVC decline exists during

MVC-relative tasks that include different intensity isometric exertions and rest, allowing recovery from muscle fatigue. Considering the intensity of the exertion performed immediately prior to obtaining an RPF value, in addition to the RPF value, improves the ability to predict MVC decline. Overall, the results from this study indicate that the RPF scale may provide a simple, noninvasive method to estimate the fatigue-induced reduction in force generating capacity of skeletal muscle for use with complex tasks observed in the workplace, athletics, or training environments.

Declaration of Competing Interest

The authors declared that there is no conflict of interest.

Acknowledgements

This work was supported by Automotive Partnership Canada (APCPJ 412476-11) and the United States Council for Automotive Research (USCAR).

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jelekin.2019.05.012.

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