# Comparison of neural excitation measures from the surface electromyogram during rate-dependent muscle contractions

Micah D. Josephson

Shenandoah University, Department of Exercise Science

Christopher A. Knight

University of Delaware, Department of Kinesiology and Applied Physiology

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Corresponding author:

Christopher A. Knight

caknight@udel.edu

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**Abstract**

Peak power and peak rate of isometric force development (RFD) predict performance and functional mobility. Surface electromyography (EMG) is used to quantify the amplitude and rate of neuromuscular excitation. To inform the selection of EMG measures in research on rate-dependent muscle contractions, this methodological study compared amplitude-, area- and rate-based measures based on their correlations with RFD. Considering populations in whom a quiet EMG baseline is challenging, we included measures that do not require the determination of EMG onset. Twenty-one young adults performed isometric dorsiflexion contractions to 40% of their maximal force at increasing RFD. EMG was recorded from tibialis anterior. Relationships between EMG measures and RFD were quantified with Spearman's rho. RMS amplitude of the initial 75ms of EMG had the strongest correlation with peak RFD ($\rho$=0.80) among measures computed from EMG onset. Peak rate of EMG rise (RER) had the strongest relationship with peak RFD ($\rho$=0.69) among measures that did not require determination of EMG onset. The strength of the relationship between RER and RFD and the strong correlation between RER and RMS75 during rapid contractions ($\rho$=0.86) supports the use of RER in experiments where neural excitation might not be initiated from a quiet baseline.

## 1. Introduction

The neural excitation of muscle is examined with surface electromyography (EMG) to understand neuromuscular control mechanisms (Zehr and Sale, 1994) and patterns of muscle involvement during movement (Sanderson et al., 2006). Studies have examined how such factors are modified by aging (Klass et al., 2008), physical activity (Laroche et al., 2007), fatigue (Bigland-Ritchie, 1981), movement disorders (Berardelli et al., 1996), chronic conditions (Chou et al., 2013), injury (Wang et al., 2015), and exercise training in healthy adults (Aagaard et al., 2002) and clinical populations (David et al., 2016). The amount of myoelectric activity detected with EMG represents the sum of the motor unit action potentials (MUAP) which is primarily determined by motor unit recruitment and rate coding mechanisms and influenced by other factors. Such factors include, but are not limited to, the filtering effects of soft tissue, electrode movement in dynamic conditions and amplitude cancellation. Relatively high variance in EMG measures necessitates the use of optimal methods and careful selection of dependent measures.

Kinesiologists are increasingly interested in mechanical power and rates of muscle force development (RFD) as predictors of function and mobility (Hazell et al., 2007; Sayers and Gibson, 2010). Accordingly, studies have focused on the *rate* of neural excitation during rapid isometric contractions (Aagaard et al., 2002; Chou et al., 2013; Van Cutsem et al., 1998). Across such studies, a variety of measures are used to quantify *initial* neural excitation rate at the onset of an EMG burst and/or *peak* neural excitation rate. Amplitude and area under the curve (definite integral, AUC) measures are often calculated over different periods of myoelectric activity and a peak rate of EMG rise (RER) measure calculated from the derivative of the rectified and smoothed electromyogram is used with increasing frequency (Aagaard et al., 2002; Chou et al., 2013; de Paula et al., 2017). Peak RER offers the advantage that there is no requirement to determine EMG onset and it can be applied in conditions with no quiet

EMG baseline. For example, the onset of an EMG burst during a rapid contraction is difficult to determine amidst EMG bursts that are due to Parkinson's tremor.

Root Mean Square (RMS) amplitude and AUC measures have been used extensively to quantify the *magnitude* of neural excitation in the study of maximal strength and gait analysis and technical guidance can be found in references on EMG practice (Kamen and Gabriel, 2010; Winter, 1990). However, the use of EMG measures to quantify the *rate* of neural excitation in rate-dependent muscle contractions is less developed and no reference on EMG practice currently describes rate-specific measures categorically. The aim of this methodological study was to provide empirical guidance for the selection of measures to quantify neural excitation during rate-dependent force production. Submaximal rapid isometric muscle contractions were performed in ankle dorsiflexion across a wide range of rates of force development. Surface electromyograms were obtained from the tibialis anterior muscle. Candidate EMG measures were evaluated based on their correlations with peak RFD, average RFD and time to peak force. We anticipated that some measures would bear greater correlations with mechanical output while some sets of measures would have trivial differences due to their mathematical similarity.

## 2. Methods

### *2.1 Participants*

Twenty-one young adult university students, ten females and eleven males, (mean $\pm$ SD: age=21.8 $\pm$2.8 years; body mass = 72.8 $\pm$ 19.7 kg; height=1.7 $\pm$ .1 m) participated in this study. All participants were free of neurological deficit/disorder and lower body dysfunction and signed a university approved informed consent before beginning the study.

### *2.2 Procedures*

Data were collected during a single testing session using DASYlab v.13 software (National Instruments, Austin, TX) to control acquisition and provide real time feedback of isometric force. Participants were seated on a custom bench with the ankle in 20 degrees of plantar flexion, which approximates the position for peak isometric dorsiflexion torque production (Hasson et al., 2011; Marsh et al., 1981). The foot of the dominant leg was fastened with a non-elastic buckle strap to a plate affixed to a strain gauge force transducer (Model sm-100, Interface Force Inc., Scottsdale, AZ). Force was amplified and hardware filtered (low pass, 50Hz) in real-time (Model SGA, Interface force Inc., Scottsdale, AZ). The skin above the tibialis anterior was shaved and cleansed with ethyl alcohol. A pre-amplified double differential surface electrode was secured to the skin above the mid-belly region of the tibialis anterior (MA-300, Motion Lab Systems, Baton Rouge, LA). Electrode surfaces were medical grade stainless steel disks with 12mm diameter, 17mm inter-electrode distance, and a 13x3mm bar separating the sensors as a reference contact. Amplification ranged from 2000 to 5700. Input impedance for this system is > 100 MΩ with a common mode rejection ratio > 100 dB at 65Hz and noise < 1.2uV RMS. Signals were digitized at 2kHz with 24-bit resolution (CDAQ-9178 and NI9239, National Instruments, Austin TX). Participants performed three maximum voluntary isometric contractions (MVC) separated by two minutes of rest. The maximum force achieved was used to present relative force levels (%MVC) in visual feedback. In ramp conditions, participants were instructed to overlay a real time plot of their force onto a static plot of the prescribed RFD condition. Visual feedback was provided on a video monitor (61cm diagonal screen size) positioned at eye level approximately 1.3m away.

Each trial included a different experimental condition (described below). During the ramp conditions, the resolution was 4.44%MVC/cm (vertical) by 0.53s/cm (horizontal). During the rapid force pulse condition, visual feedback was a vertical bar graph of their relative force level (vertical resolution = 3.75%MVC/cm). Instructions were to 'hit the approximate 40%MVC force level as quickly as possible without focusing on accuracy' because speed is sacrificed for greater accuracy (Gordon and Ghez, 1987).

*2.3. Experimental Conditions*

A trial consisted of either five to seven ramp force-time curves to 40% MVC with rates of force development of 20%MVC/s, 40%MVC/s, 80%MVC/s, 160%MVC/s, and 200%MVC/s or sets of rapid force pulses. The ramp trials had a sawtooth pattern with each ramp separated by two seconds. Rapid force pulses were separated by one second. All trials were thirty seconds in duration with at least one minute between. For analysis, the participant's ability to transition from a resting force level to a linear increase in force with the prescribed slope was important. Therefore, based on visual inspection by the investigator, participants performed each rate of force development condition until five ramps of adequate performance were obtained. There was no separate practice phase prior to recording. The order of ramp conditions was counterbalanced across participants to reduce the possible effects of order, fatigue or muscle potentiation. Two trials of rapid force pulses were performed last.

*2.4. Data processing*

Force and EMG data were processed using LABview v 2014 (National Instruments, Austin, TX) and results were visually inspected using custom routines (Matlab, Mathworks, Natick, MA). Absolute strength scores are reported in Newtons (N) and, for analysis, the forces were converted to a percent of MVC force. Rate of force development was calculated from the force-time curve as a central tendency slope of a .1s moving window.

Electromyograms were adjusted for gain, de-trended and full-wave rectified (absolute value). Maximum EMG from the MVC contractions was calculated as the RMS amplitude of the recording surrounding peak MVC force (EMGmx, $\pm$ .250s window) and reported in millivolts (mV). Root mean square and integral (Q) measures were calculated from the rectified EMG and normalized to the EMGmx. A zero-lag $4^{th}$ order low-pass Butterworth filter with a 20Hz cutoff was used to create a linear

143 envelope of the EMG and EMGmx was recalculated to reflect the smoothing (EMGmxs). Rate of EMG
144 rise (RER) was calculated from the linear envelope of the EMG as a central tendency slope of a .1s
145 moving window and normalized to EMGmxs. User-interactive routines were written to graphically
146 display the signals of interest and calculate the dependent measures after selection of suitable ramps or
147 pulses for analysis. Automatically determined landmarks were confirmed or corrected. The user
148 selected ramp contractions for analysis based on the quality of the transition from rest to the rising
149 slope of the given condition. Ramps where force was initiated too abruptly resulting in EMG spikes and
150 RFD responses that were not consistent with the specified condition were excluded from analysis.
151 Force, RFD, EMG, and RER signals were plotted for visual inspection during analysis of all
152 contractions (Figures 1 and 2). Markers identifying force initiation, peak force, peak RFD, EMG onset,
153 peak EMG, and peak RER were inspected for accuracy and manually adjusted if necessary. The
154 threshold for the onset of force production and EMG onset was determined as the mean plus three
155 standard deviations of a quiet baseline (Clark et al., 2011). Force measures include: peak force (PF),
156 peak RFD (RFDPk), and average RFD (RFDavg). All EMG measures were taken from points prior to peak
157 force and include: peak EMG amplitude (from unfiltered and smoothed data, EMGPk, EMGPks), peak
158 RER (RERPk), RMS amplitude computed over 30, 50 and 75ms following EMG onset (RMS30, RMS50,
159 RMS75) and computed backwards from the instance of RFDPk (RMS30b, RMS50b, RMS75b), EMG AUC
160 in the initial 30, 50 and 75ms following EMG onset (Q30, Q50, Q75) and computed backwards from the
161 instance of RFDPk (Q30b, Q50b, Q75b). The 75ms upper limit of EMG calculations was based on
162 evidence that neural excitation has the prevailing influence on RFD to this point and contractile factors
163 begin to dominate thereafter (Maffiuletti et al., 2016). The variables computed backwards from RFDPk
164 were explored in search of alternate measures that would not require the determination of EMG onset,
165 which can be sensitive to the chosen methodological approach in healthy individuals (Maffiuletti et al.,
166 2016) and likely to be a greater challenge in people with movement disorders. Root mean square and Q

were also calculated from EMG onset to PF (RMS-PF, Q-PF) and from EMG onset to RFDPk (RMS-RFD, Q-RFD). Timing variables of interest include: time to peak RER (TRERPk), time to peak RFD (TRFDPk) and time to peak force (TPF).

*2.5. Statistical analysis*

The Statistical Package for Social Sciences (SPSS v24, IBM, Armonk, NY) was used for data analysis. Spearman's ρ correlation was used to describe relationships between measures because visual inspection revealed many instances of skewed distributions and heteroskedasticity. Considering the assumed application to research on rapid muscle contractions, analyses were conducted separately for all contractions (n=1081), and for the subset of contractions with an average RFD greater than 220 %MVC/s (n=249), which will be referred to as rapid, hereafter. In text values are reported as means ± standard deviations.

## 3. Results

The mean dorsiflexion strength of 154.7 ± 33.2N is consistent with other reports (Carroll et al., 2013). In the subset of rapid contractions RFDavg was 283 ± 44 %MVC/s, RFDPk was 385 ± 55 %MVC/s and TPF was 161 ± 25ms. The RFD measures are within the range of values shown for rapid dorsiflexion to 40 %MVC in Figure 1 of Van Cutsem et al. (Van Cutsem et al., 1998) and the present time to peak force is slower than their pre-training value of 135.8ms, which was obtained from the five fastest contractions in each of their subjects.

For each fixed-duration of computation (30, 50, 75 ms), RMS and Q measures were strongly correlated with each other in all contractions (ρ>.988) and in the subset of rapid pulses (ρ>.981). This redundancy is to be expected because integral measures computed over fixed periods of time are essentially expressions of mean amplitude. For efficiency, only the fixed-duration RMS measures, rather

than Q, will be emphasized from here forward but without any conclusion about the superiority of either measure.

Median TRFDPk was 123ms and 69ms in all and rapid contractions respectively. As RFDAvg increased, there was greater temporal coupling between RERPk and RFDPk with the standard deviations of the time between RERPk and RFDPk decreasing from 384ms in all contractions to 16ms in rapid (Figure 3). In rapid contractions, RERPk preceded RFDPk by a median value of 73.5ms. This duration is a relevant consideration for the variables that are calculated either forward from EMG onset or backwards from the instance of RFDPk.

Table 1 contains Spearman's ρ values for relationships between each EMG measure and RFDPk or TPF for all contractions and for rapid contractions. In all and rapid contractions, the correlations between RFDPk and TPF were ρ=-.974 and ρ=-.697, respectively. Using an average of the Fisher transformed correlations involving all EMG variables, the magnitude of correlations is substantially less for rapid contractions (ρ=.371 vs. ρ =.617) due to a restricted range effect (Bland and Altman, 2011). Nevertheless, the relative strength of these correlations remains important to consider, especially for research involving rapid isometric contractions. However, if generalizations to clinical populations such as stroke are of interest, the correlations from data including slower RFD conditions may be more relevant.

For the set of all contractions, negative correlations with peak RFD were observed for Q-PF and Q-RFD and positive correlations were observed for the corresponding TPF. These observations could be misleading. The slowest ramp contractions required a prolonged period of neural excitation resulting in greater AUC due to increased duration rather than amplitude. Root-mean-square computed to peak rate of force development had greater correlations with RFD and TPF than RMS-PF. Overall, RMS75 tended to have the strongest correlations with RFD and TPF but in the subset of rapid contractions RMS50 was practically equivalent. Peak rate of EMG rise had the greatest correlation among the

variables not reliant on EMG onset and was superior to the variables calculated backwards from the instance of RFDPk. While measures of peak EMG computed from smoothed EMG had greater correlations than those computed from raw EMG, both peak EMG measures had among the weakest correlations with RFD and TPF.

Table 2 contains the correlations among the EMG measures for all contractions (below the diagonal) and for rapid pulses (above the diagonal). Several correlations among variables are strong as one would expect given their similarity. Root-mean-square 75 and RERPk, the two variables bearing stronger correlations with contraction rate, are correlated at $\rho$=.75 and $\rho$=.86 for all and rapid contractions, respectively. While related, these two variables also carry some amount of unique variance.

## 4. Discussion

Based on isometric dorsiflexion contractions to a force level of 40%MVC, performed across a continuum of rates of force development, we hypothesized that some measures of neural excitation would bear stronger relationships with mechanical output measures and other measures would show similar relationships with mechanical measures based on similarities in their calculation. Using the full set of data, relatively strong correlations were observed between several EMG measures and the two mechanical measures of primary interest (peak RFD and time to peak force). A subset of rapid contractions (RFDAvg >220 %MVC/s) was analyzed separately because most hypotheses related to RFD involve maximal rate contractions (often referred to as rapid, ballistic, or explosive force production). In rapid contractions, the correlations were lower overall but there was general consistency among the ranking of measures highlighted.

Root-mean-square 75 and RERPk are emphasized due to relatively high correlations with peak RFD and meaningful differences in their computation. Root-mean-square 75 is an amplitude measure

239 that requires the determination of EMG onset. Peak RER is a true rate measure as it is the derivative of
240 the rectified and smoothed electromyogram. A continuous RER signal can be computed for the entire
241 electromyogram of interest and determination of peak RER does not rely on the prior determination of
242 EMG onset. Thus, issues related to criteria for EMG thresholds and technical or physiological challenges
243 related to a quiet baseline can be avoided.

244 The ultimate consideration in selecting electromyographic variables is their suitability for a given
245 hypothesis. EMG measures that require EMG onset determination, such as RMS75, will be challenging
246 in individuals with Parkinsonian tremor or spasticity. Further, in continuous movement conditions, such
247 as gait or bicycling, a muscle may not consistently exhibit a quiet baseline. In these cases, a measure like
248 RERPk has a distinct advantage. Among the tested measures that do not require EMG onset,
249 correlations between peak RER and peak RFD were superior. While RER appears less frequently than
250 RMS and Q in the literature, an increasing number of studies support the validity of the measure. For
251 example, decreases in RER have been associated with reduced RFD due to fatigue (Morel et al., 2015)
252 and eccentric exercise (Farup et al., 2016). However, similar to RMS and Q measures, some have
253 calculated average RER for fixed windows of time (Farup et al., 2016), eliminating the advantage of RER
254 as a measure that does not require EMG onset determination.

255 The present results favored calculations of RMS and Q measures over the longer duration (75 vs.
256 30 and 50 ms) following EMG onset. This was not surprising considering the association between this
257 period and a greater neural contribution to RFD (Maffiuletti et al., 2016). Root-mean-square amplitude
258 was superior to Q for measures that were bounded in time by the achievement of RFDPk or PF. The
259 slower ramp contractions represented a special case for this calculation of Q because increased area
260 under the curve was due to prolonged neural excitation rather than greater neural excitation (see
261 negative correlations with RFD for Q-RFD and Q-PF in Table 1). This is a meaningful consideration for
262 conditions, such as stroke, in which severe restrictions in peak motor unit firing rates have been

observed (Chou et al., 2013). Without the ability to produce high instantaneous firing rates in rapid contractions, some individuals with stroke exhibited prolonged motor unit firing (more total spikes) to reach a target force. With a varied duration of calculation in such conditions, a greater area under the rectified EMG can represent either greater firing rates and/or recruitment (high amplitude EMG, short duration) or impairment (low amplitude EMG, long duration). In contrast, RMS-RFD, RMS-PF or RERPk are temporally unconstrained measures that would more faithfully represent the quality of neural excitation compared to AUC measures.

Even though RMS75 (and Q75) were more strongly correlated with peak RFD than corresponding measures computed over 30 or 50ms, we do not suggest that these latter measures are flawed or that a minimal set of measures must be used. Some have effectively used comprehensive sets of serial measures calculated from onset to 30-100ms (or greater) to test hypotheses about the temporal patterns in neural excitation with respect to RFD and how they might change with training in young (Aagaard et al., 2002) and older (Barry et al., 2005) adults. While methodological recommendations would be simplified by empirical support for a small set of measures, the absence of a clearly distinct set of measures can also be viewed positively. Numerous studies have examined the role of neural excitation in rapid contractions using a variety of measures represented by those selected for this project (e.g. Aagaard et al., 2002; Clark et al., 2014; David et al., 2016; Inglis et al., 2017). Strong correlations among EMG measures can provide some confidence that non-significant findings in various studies were not necessarily due to the selection of the wrong measure. For example, the choice of RMS or Q seems inconsequential for calculation over fixed window sizes. However, the present results indicate that peak EMG amplitude is a questionable measure compared to the others if one is interested in the neural correlates of rate-dependent function.

Compared to most publications involving rapid contractions (c.f. Aagaard et al., 2002; Clark et al., 2011; Folland et al., 2014; Inglis et al., 2017), the use of a wide range of RFD conditions in the

present study provided the opportunity to observe key features of the transition from slow, closed-loop, force production (ramps) to fast, open-loop, force production (pulses). When Freund and Budingen (1978) explained their interest in maximal rate isometric and isotonic conditions, they cited the benefit of a system's invariance when it is operating against the limits of its function. Figure 3 shows one of multiple measures (time to peak RER) that exemplified the transition to relatively invariant system behavior as the rate of force development increased. While others have demonstrated invariant or nearly invariant time to peak force in rapid force pulses of varied amplitudes (Freund and Büdingen, 1978; Gordon and Ghez, 1987), there has been little systematic inquiry into the rates at which neuromuscular control mechanisms achieve this state of invariance or the implications for optimal human performance and disease. Other measures with similar patterns of diminished variance included time to peak force, time to peak RFD and the time between peak RER and peak RFD. It might be the case that the ability to generate high initial firing rates is a necessary component of this invariance.

One might consider the possible influences of muscle fatigue or potentiation on the results of this study. While both physiological factors are known to affect RFD (HÄkkinen and Komi, 1986; Maffiuletti et al., 2016), the strength of the present study design is that it compares correlations between candidate EMG measures and RFD taken from a single, relatively large dataset, and the effects would be common to all measures tested. Generalizations of the present findings beyond healthy young adults and outside of the tibialis anterior muscle should be made with caution and one should consider whether the present findings are generalizable to dynamic conditions or to force levels greater than 40% MVC, where rates of neural excitation and force development are greater. Continued methodological development related to these considerations may be warranted. Furthermore, we report findings on onset-based EMG measures that could vary depending on the chosen method of threshold determination. In the slowest contractions of the present study, initial neural excitation was less pronounced and more user intervention in the determination of EMG onset was required.

## 5. Conclusion

We examined multiple EMG measures to determine whether specific measures would have greater correlations with peak rate of force development. Of particular interest was establishing whether peak rate of EMG rise (RER) would have relationships with peak RFD that are comparable with measures computed in specific windows following EMG onset. The results support the use of RER in the study of rapid contractions in conditions such as Parkinson's disease where tremor sometimes hinders the determination of EMG onset. While RMS75 had the strongest correlations with peak RFD, RER was the strongest non-onset based alternative among the measures tested.

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Table 1: Spearman's correlations between EMG measures and Peak RFD and Time to Peak Force (TPF) computed for all data and the subset of rapid contractions. Bold and italicized measures are emphasized due to their favorable associations with peak RFD and different methods of computation.

| All Data (n=1081) | | | RFD Avg > 220 %MVC/s (n=249) | | |
|---|---|---|---|---|---|
| | RFD Pk. | TPF | | RFD Pk. | TPF |
| ***RMS75*** | ***0.80*** | ***-0.81*** | ***RMS75*** | ***0.52*** | ***-0.54*** |
| RMS-RFD | 0.74 | -0.72 | ***RMS50*** | ***0.51*** | ***-0.56*** |
| RMS50 | 0.71 | -0.72 | ***RERPk*** | ***0.48*** | ***-0.40*** |
| ***RERPk*** | ***0.69*** | ***-0.66*** | RMS-RFD | 0.45 | -0.33 |
| RMS30 | 0.60 | -0.62 | RMS50B | 0.43 | -0.27 |
| RMS75B | 0.58 | -0.54 | RMS30 | 0.43 | -0.50 |
| RMS50B | 0.58 | -0.54 | RMS-PF | 0.41 | -0.22 |
| RMS30B | 0.55 | -0.52 | RMS30B | 0.39 | -0.21 |
| RMS-PF | 0.52 | -0.49 | RMS75B | 0.38 | -0.22 |
| EMGPks | 0.32 | -0.28 | EMGPks | 0.37 | -.23 |
| EMGPk | 0.23 | -0.19 | EMGPk | 0.32 | -0.17 |
| Q-RFD | -0.25 | 0.28 | Q-RFD | 0.22 | -0.01 |
| Q-PF | -0.78 | 0.82 | Q-PF | 0.10 | 0.19 |

Table 2: Spearman correlations between all measures. Correlations calculated from all contractions are below the diagonal and correlations for the subset of rapid contractions (RFDAvg > 220 %MVC/s) are above the diagonal.

| | RMS30 | RMS50 | RMS75 | RMS-RFD | RMS-PF | Q-RFD | Q-PF | RERPk | EMGPk | RMS30B | RMS50B | RMS75B |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RMS30 | | 0.81 | 0.71 | 0.60 | 0.53 | 0.42 | 0.30 | 0.51 | 0.44 | 0.44 | 0.48 | 0.51 |
| RMS50 | 0.88 | | 0.89 | 0.72 | 0.62 | 0.49 | 0.33 | 0.68 | 0.53 | 0.49 | 0.58 | 0.62 |
| RMS75 | 0.82 | 0.94 | | 0.86 | 0.75 | 0.62 | 0.45 | 0.86 | 0.68 | 0.59 | 0.74 | 0.77 |
| RMS-RFD | 0.68 | 0.74 | 0.80 | | 0.95 | 0.89 | 0.74 | 0.93 | 0.88 | 0.86 | 0.96 | 0.98 |
| RMS-PF | 0.60 | 0.61 | 0.64 | 0.88 | | 0.91 | 0.87 | 0.86 | 0.90 | 0.86 | 0.93 | 0.96 |
| Q-RFD | 0.01 | -0.05 | -0.10 | 0.30 | 0.31 | | 0.89 | 0.78 | 0.82 | 0.85 | 0.89 | 0.94 |
| Q-PF | -0.33 | -0.45 | -0.52 | -0.28 | 0.03 | 0.54 | | 0.62 | 0.76 | 0.74 | 0.75 | 0.80 |
| RERPk | 0.62 | 0.70 | 0.75 | 0.87 | 0.83 | 0.15 | -0.25 | | 0.80 | 0.73 | 0.88 | 0.91 |
| EMGPk | 0.39 | 0.38 | 0.39 | 0.66 | 0.84 | 0.41 | 0.26 | 0.68 | | 0.79 | 0.88 | 0.89 |
| RMS30B | 0.50 | 0.54 | 0.58 | 0.89 | 0.81 | 0.47 | -0.09 | 0.75 | 0.66 | | 0.91 | 0.88 |
| RMS50B | 0.53 | 0.57 | 0.61 | 0.93 | 0.84 | 0.48 | -0.10 | 0.80 | 0.70 | 0.95 | | 0.97 |
| RMS75B | 0.54 | 0.58 | 0.63 | 0.95 | 0.86 | 0.50 | -0.09 | 0.82 | 0.71 | 0.93 | 0.98 | |

410

411 Figure Captions

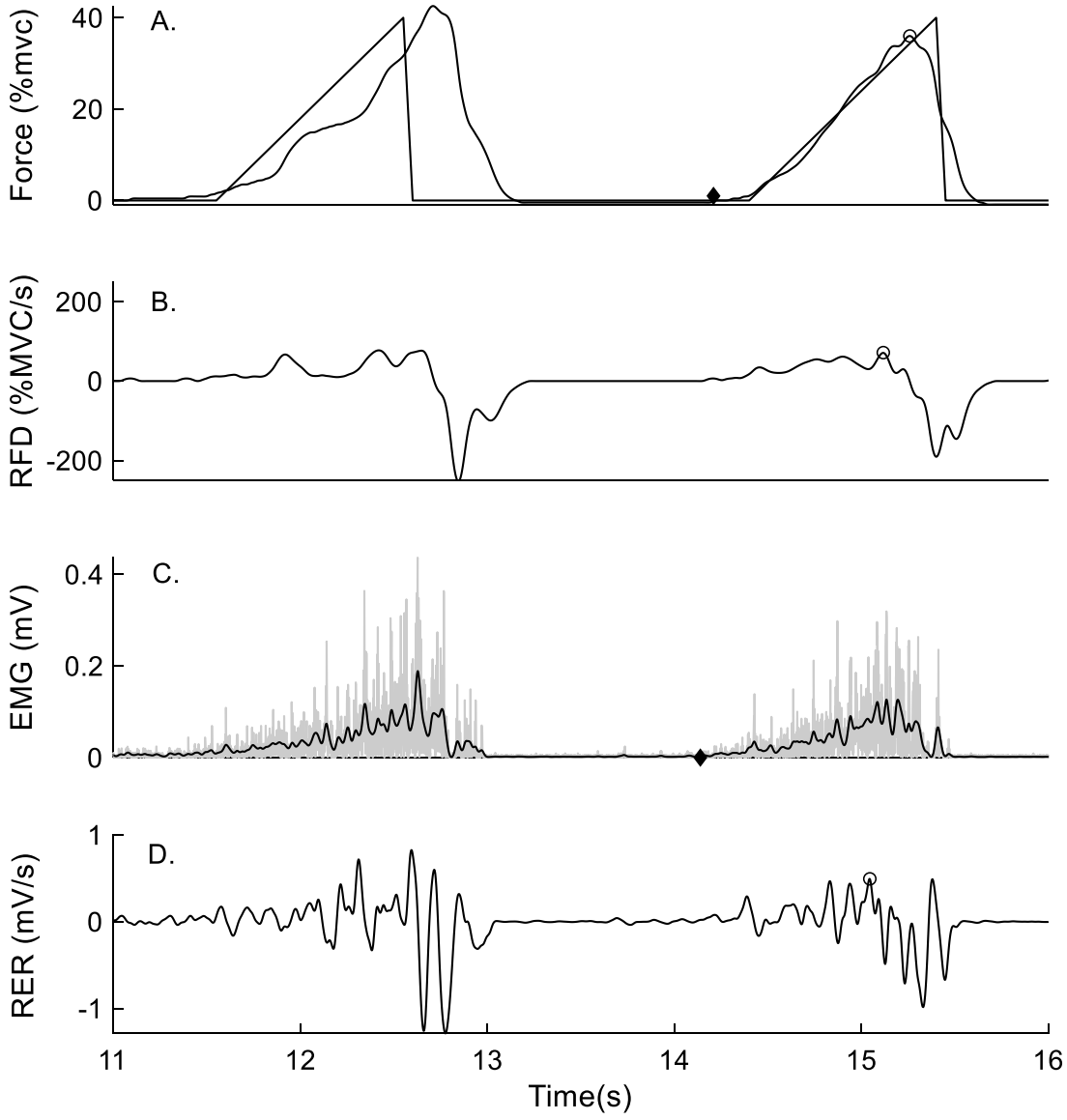
412 Figure 1. Ramp contraction data processing (40%MVC/s condition). A) Plot of the subject's force
413 superimposed on the static plot to match. The diamond marks force onset and the circle marks peak
414 force. B) Plot of rate of force development (RFD). The circle marks peak RFD. C) Plot of rectified EMG
415 with (black line) and without (gray line) smoothing by a low pass filter. The diamond marks EMG onset.
416 D) Plot of rate of EMG rise (RER). The circle marks peak RER. Based on visual inspection of the transition
417 from rest to the prescribed RFD, only the ramp on the right was selected for analysis.

418 Figure 2. Rapid force pulse data processing. Top: Isometric force (thin unimodal line), rectified EMG
419 burst (thin gray line) and rectified and smoothed EMG burst (thick line). a = peak force, b = peak EMG,
420 and c = peak smoothed EMG. Bottom: Rate of force development (RFD, thin line) and rate of EMG rise
421 (RER, thick line). d = peak RFD and e = peak RER. Gray bars illustrate the 30, 50 and 75 ms windows used
422 to compute EMG RMS and Q measures forward from EMG onset (left bars) and backward from the
423 instance of peak RFD (right bars).

424 Figure 3. Scatter plot of time to peak RER against peak RFD showing an example of the relative
425 invariance in neural excitation that occurs above approximately 220 %MVC/s.

426

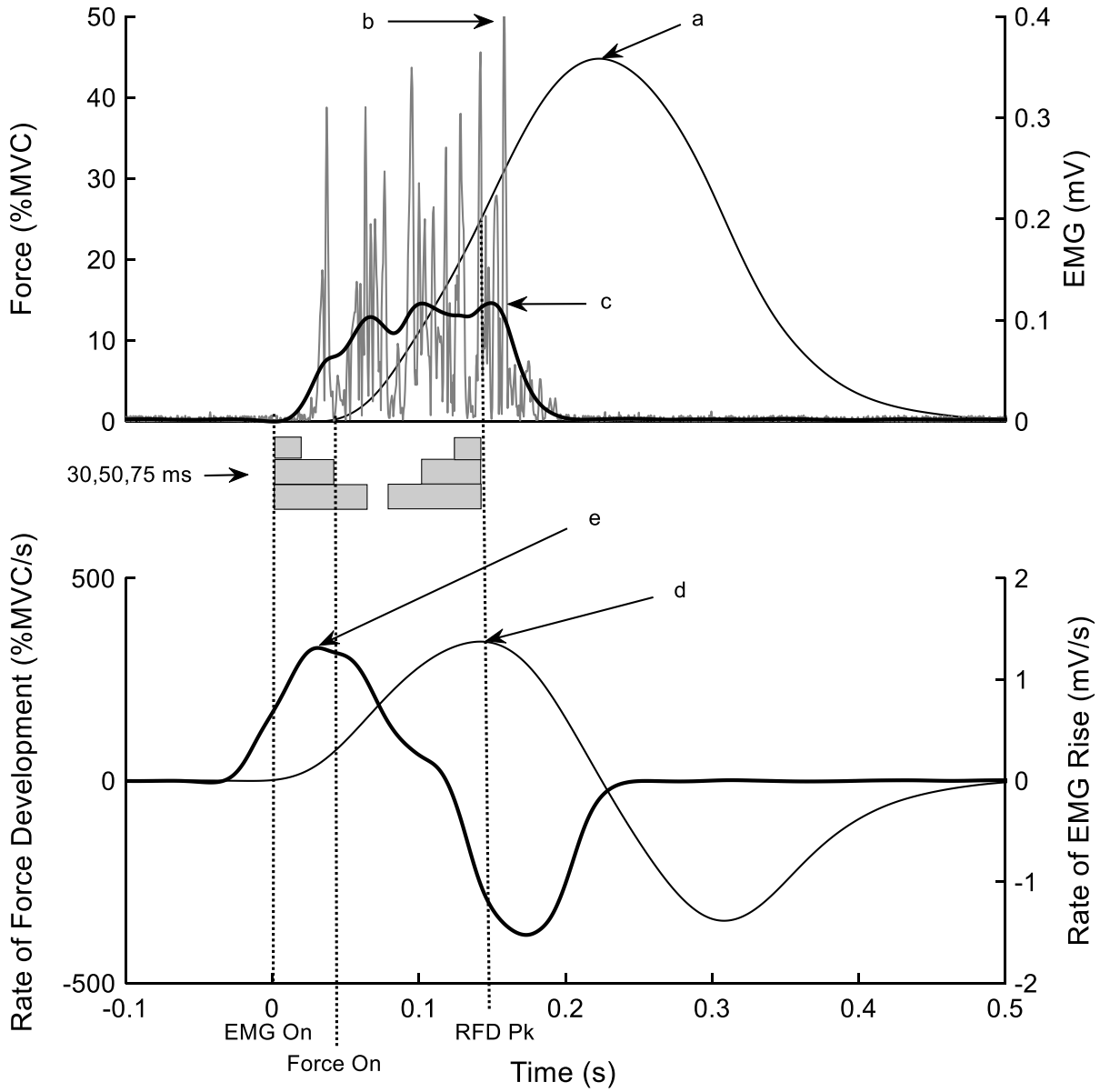
427

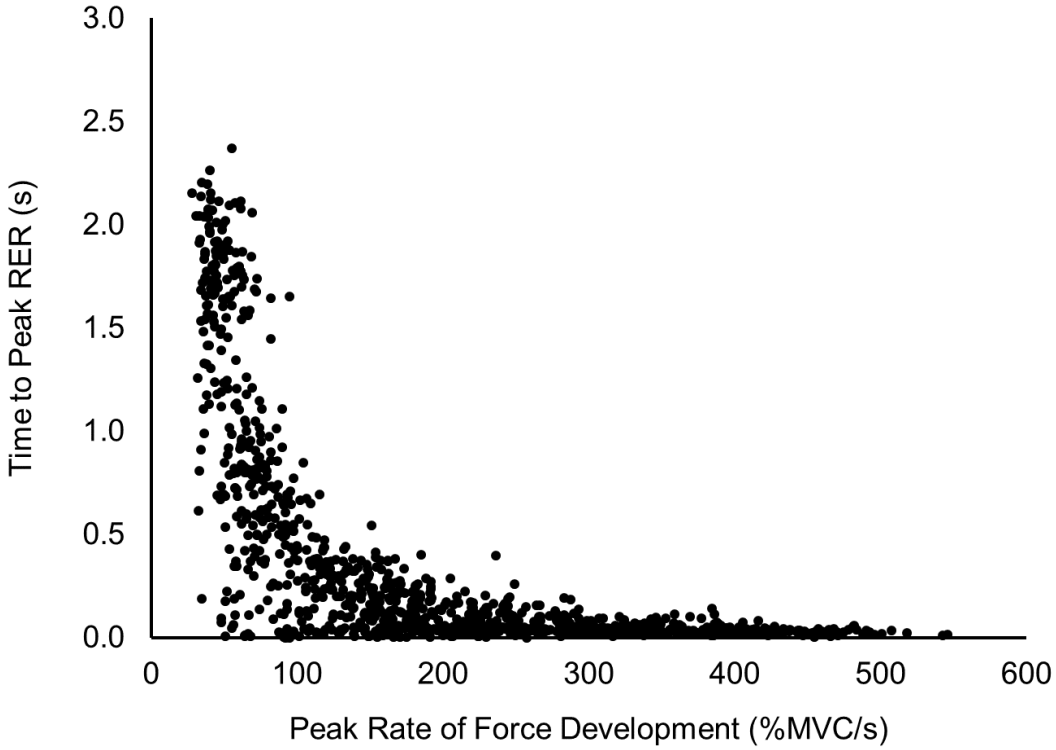

A.
Force (%mvc)
40
20
0
B.
RFD (%MVC/s)
200
0
-200
C.
EMG (mV)
0.4
0.2
0
D.
RER (mV/s)
1
0
-1
11
12
13
14
15
16
Time(s)

428

429

430


Force (%MVC)
EMG (mV)
b
a
c
30,50,75 ms
e
d
Rate of Force Development (%MVC/s)
Rate of EMG Rise (mV/s)
EMG On
Force On
RFD Pk
Time (s)


3.0
2.5
2.0
1.5
1.0
0.5
0.0
Time to Peak RER (s)
0
100
200
300
400
500
600
Peak Rate of Force Development (%MVC/s)