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ORIGINAL ARTICLE

# A novel method to assess rate of force relaxation: reliability and comparisons with rate of force development across various muscles

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## Abstract

**Purpose** The ability to generate quick submaximal muscle forces followed by quick relaxations is essential for various athletic and daily tasks. While force generation has been studied extensively, the studies of force relaxation are scarce. Therefore, we aimed to develop the rate of force relaxation scaling factor (RFR-SF) as a kinetic variable to assess the ability to relax submaximal muscle forces quickly.

**Methods** Thirteen young adults performed rapid isometric force pulses to various submaximal levels in two different sessions. We compared RFR-SF with rate of development scaling factor (RFD-SF) in grip force muscles (GF), elbow (EE), and knee extensors (KE) and tested its reliability. Both RFD-SF and RFR-SF were calculated as the slopes of the linear relationship between peak forces and the corresponding peak rates of force development and relaxation, respectively.

**Results** RFR-SFs were mainly different among the tested muscle groups (GF 8.22 ± 0.76 1/s; EE 7.64 ± 0.92 1/s; KE 6.01 ± 1.75 1/s) and there was no correlation among them (all $p > 0.05$). Within each tested muscle group, RFR-SF was lower than RFD-SF (GF 9.29 ± 1.05 1/s; EE 10.75 ± 0.87 1/s; KE 9.66 ± 0.89 1/s; all $p < 0.001$). The reliability of RFR-SF was moderate to good across the tested muscles (ICCs between 0.54 and 0.76 and all CVs < 15%).

**Conclusion** The RFR-SF is a clinically relevant kinetic variable that can reliably quantify the ability to relax a muscle force quickly. Future studies should assess both RFD-SF and RFR-SF as they represent different properties of the neuromuscular system.

**Keywords** Rate of force development · Isometric · Power · Half-relaxation · Clinical · Sports

## Introduction

Quick muscle contractions followed by quick relaxations are essential in various tasks that include athletic movements, postural corrections, and cyclical tasks such as walking and running. Therefore, the ability to quickly relax a muscle contraction is arguably as important as the ability to generate a quick muscle contraction in movements that require powerful, yet, submaximal contractions. While previous research has extensively studied the ability to produce quick force production [for review see (Maffiuletti et al. 2016)], the ability of muscles to relax has been largely neglected.

The ability to produce quick muscle force has traditionally been evaluated through isometric force production tasks that require the generation of a high level of muscle force as quickly as possible (Maffiuletti et al. 2016). The highest rate (i.e., highest slope) of the produced force is named as the maximum rate of force development (RFD). While the functional relevance of maximum RFD is inevitable in some sports activities, an ability to produce a high yet submaximal RFD could be functionally more relevant in daily tasks in both healthy and patient populations (e.g., generating reaction forces over an external support and making postural corrections). Recently, rate of force development scaling factor (RFD-SF) has been introduced as a robust measure of neuromuscular quickness that can quantify the ability to

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generate high rates of force development across submaximal force ranges (Bellumori et al. 2011). It is calculated in brief isometric force production tasks and calculated as the slope of the regression line between the peak values of the force pulses performed to various submaximal force levels and their corresponding peak RFDs. The R-squared ($R^2$) obtained from the same relationship indicates the consistency of the scaling of RFD with the magnitude of the produced force. In healthy young adults and across the various tested muscle groups, a high RFD-SF along with $R^2$ values close to one was found (Bellumori et al. 2011; Casartelli et al. 2014; Haberland and Uygur 2017). This indicates invariance in the time required to reach peak force regardless of its amplitude (Freund and Budingen 1978; Gordon and Ghez 1987). Unlike maximum RFD, RFD-SF is relatively invariant across muscles of different sizes and strengths (e.g., RFD-SF of index finger abductors, elbow and knee extensors were 8.2, 8.9, and 8.3 1/s, respectively), similar in both genders, and can be assessed either from absolute or relative values of force or torque (Bellumori et al. 2011; Casartelli et al. 2014). Moreover, it is sensitive enough to quantify the differences among various populations (e.g., people with neurological diseases, older adults) (Klass et al. 2008; Chou et al. 2013; Bellumori et al. 2013) and neuromuscular adaptations to power training (Van Cutsem et al. 1998; Bellumori et al. 2017). Therefore, RFD-SF has been suggested as a viable alternative to maximum RFD to assess an individual's neuromuscular quickness across a range of functional submaximal levels (Bellumori et al. 2011).

Quick force relaxation is as functionally important as quick force generation and could be a limiting factor for an individual to generate rapid movements in activities where consecutive agonist and antagonist muscle contractions are required. Although studies of force relaxation have received much less attention than those in force development, enough evidence exists to suggest its functional and clinical importance (Corcos et al. 1996; Robichaud et al. 2005). Previous studies have shown that the ability to quickly relax a muscle force is affected in healthy older adults and in people with neurological disorders and diseases (e.g., cerebral palsy, Parkinson's disease, multiple sclerosis). For example, the muscle relaxation speeds measured after both voluntary (Hunter et al. 2008; Molenaar et al. 2013) and stimulated contractions (Callahan and Kent-Braun 2011) in older adults were slower than those measured in young adults. In people with Parkinson's disease, a reduction in voluntary relaxation speed is found to be the most sensitive neurophysiological parameter to the clinical status of a patient (Robichaud et al. 2005) and to the changes in motor function when on and off medication (Corcos et al. 1996). Similarly, people with multiple sclerosis have shown reduced maximum rates of force relaxation after a stimulated tetanic force as compared to their control subjects, while both groups have shown similar tetanic maximum RFD (Ng et al. 2004). Finally, in children with cerebral palsy, the reductions in rapid force relaxation were found to be more prominent than the reductions in the maximum strength as compared to their counterparts (Tammik et al. 2008).

Similar to quick force generation, force relaxation can be assessed in isometric tasks during which subjects are required to relax their muscle contractions as quick as possible from either a certain submaximal or maximal level (Tammik et al. 2008). Force relaxation was usually quantified by either using maximum rate of force relaxation (i.e., the maximum value of $-\mathrm{d}F/\mathrm{d}t$) (Klass et al. 2008; Molenaar et al. 2013; Hakkinen et al. 1985) or total- or half-relaxation time (i.e., the time in which peak force falls to baseline or to 50% of its value, respectively) (Ng et al. 2004; Hakkinen et al. 1985). However, it is still not clear if the relaxation times depend on the peak values of the rapid forces produced or if the rate of force relaxation (RFR) scales with the magnitude of the peak force like RFD. Therefore, given the functional and clinical relevance of muscle relaxation, there is a need for the development of a clinically relevant kinetic variable that quantifies the ability to quickly reduce a muscle force across a range of submaximal levels.

Within this paper, our main aim was to develop the rate of force relaxation scaling factor (RFR-SF) such that it could be simultaneously assessed with RFD-SF through brief force pulses and to compare the values across various muscle groups of different maximal and functional capacities (e.g., grip force, elbow, and knee extensors) that have been commonly studied in the previous literature. Please note that due to the similarities in the calculation methods of RDR-SF with RFR-SF (see methods), the aforementioned benefits of using RFD-SF will also apply to RFR-SF. Our second aim was to study the correlations among the RFR- SFs obtained from each diverse muscle groups to reveal if the RFR-SF is either a characteristic of the neuromuscular system or if it is instead dependent on an individual muscle group. Our final aim was to test the within and between session reliability of the RFR-SF. We hypothesized that due to the potential neuromuscular differences contributing to both muscle contraction and relaxation, RFR-SF will be different than RFD-SF across the tested muscle groups. We also hypothesized that the RFR-SFs obtained from the various tested muscle groups of potentially different contractile and functional properties will not be correlated.

## Methods

### Subjects

Seven women (21.86 ± 1.68 years, 63.77 ± 5.74 kg, and 166.91 ± 7.43 cm) and 6 men (25.27 ± 6.56 years, 87.38 ± 15.15 kg, and 180.34 ± 11.58 cm) right-handed and right-legged adults participated in the study. To determine side dominance, we asked participants which hand/foot they would use to throw/kick an object to the furthest point. All subjects were free of neurological problems and were without injuries to their right arms or right legs in the past 6 months. Informed consent was obtained from all individual participants included in the study. The study protocol was approved by the institutional review board and it was conducted in accordance with the Declaration of Helsinki.

## Procedures

There were two sessions separated by 48 h and the time of testing was kept similar within subjects. Participants were asked to withdraw from strength training activities for at least 24 h before their testing sessions. In each session, grip force (GF; Fig. 1a), elbow extensors (EE; Fig. 1b), and knee extensors (KE; Fig. 1c) were tested.

GF was tested on an externally fixed and height-adjustable vertical handle that consisted of two parallel rubber covered metal plates connected by a single axis force transducer (WMC-50, Interface Inc., Scottsdale, AZ, USA). For each individual, the height of the handle was adjusted so that the elbow was at 90° of flexion. Similar to the studies of GF control (Uygur et al. 2014), subjects employed a four-finger grasp so that the contact with the grasping surfaces were made by the distal phalanges of four fingers and thumb (Fig. 1a). Subjects were instructed to keep their contact with the grasping surface at all times.

In EE testing, an externally fixed and height-adjustable pole with a secured force transducer was used (SM- 250, Interface Inc., Scottsdale, AZ, USA). Standing subjects were cuffed to the force transducer just proximal to their wrist using PVC piping and a firm rubber. The height of the pole

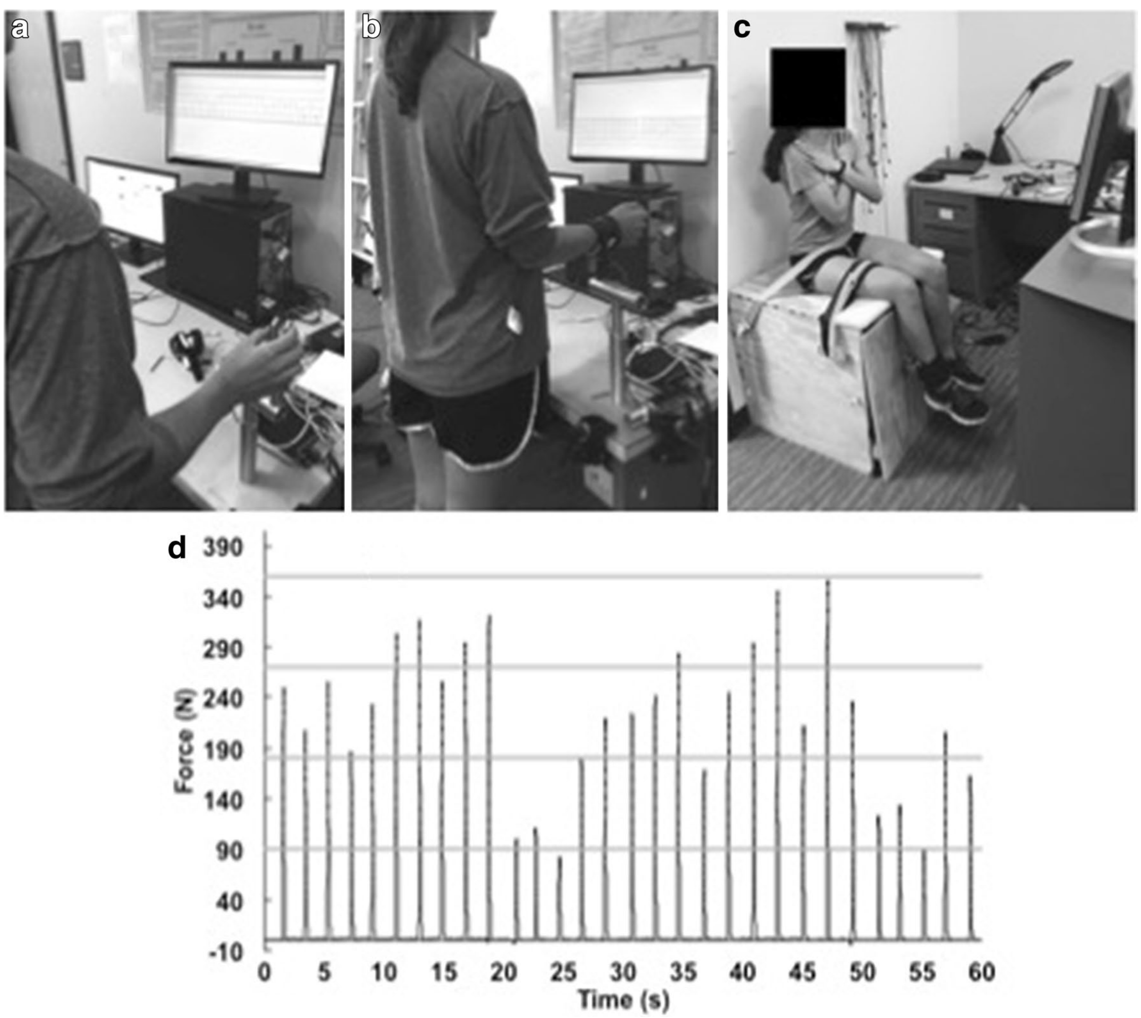


**Fig. 1** Experimental conditions. **a** Grip force. **b** Elbow extensors. **c** Knee extensors. **d** A representative raw force data from the knee extension condition. Horizontal lines represent 20, 40, 60, and 80% of the MVC

was adjusted so that their elbow was at approximately 90° of flexion. Keeping their forearm in mid-supination with hands in a fist, the subjects provided rapid forces by pushing down on the cuff towards the ground. The subjects were instructed to keep an erect body position and to use only their elbow extensors to perform the task (Fig. 1b).

In KE testing, we used a custom made wooden box with a single axis transducer attached to one of its surfaces (SM-500, Interface Inc., Scottsdale, AZ, USA). When subjects sat on the box, their knee and hip joints were at approximately 70° and 90° of flexion from full extension, respectively (Fig. 1c). A bisected PVC pipe with a firm rubber insert was attached to the transducer and wrapped around the posterior part of the distal leg. The lower legs of the subjects were cuffed to a rubber insert right above their lateral malleoli using another firm rubber pad on the anterior portion of the distal leg. Three different straps were used to both minimize the unwanted compensations and to isolate the knee extensors. The first strap was used to secure the distal leg on the transducer and was placed around the PVC pipe and the anterior firm rubber pad. The second strap was used to secure the thigh. The final strap was placed across the hips to act as a belt. Subjects were asked to cross their arms across their chest during the testing.

The baseline noises obtained from the unloaded transducers were around 0.23, 0.2, and 0.19% of the recorded maximum voluntary contraction (MVC) for GE, KE, and EE, respectively. In all testing conditions, the baseline forces applied by the relaxed subjects on the transducers were recorded and subtracted from the actual forces.

### The RFD-SF/RFR-SF Protocol

The order of the tested muscles was block randomized across subjects and it was done so that none of the subjects started their second session with the same muscle group as they had performed in the first session. In each muscle group tested, testing started with three 3-s MVC trials separated by 60 s under the instruction to squeeze (GF), pushdown (EE), or kick (KE) "as hard as" possible. Within each muscle group tested, the highest recorded MVC was used to provide feedback in brief force pulse protocol. To check if the testing protocol was associated with fatigue, MVCs of each studied muscle group was tested right after the completion of the testing protocol.

The protocol explained below was used in both sessions and for all three of the muscle groups tested. In the brief force protocol, a feedback monitor displayed four red horizontal lines corresponding to 20, 40, 60, and 80% of the recorded MVC while the actual force produced was shown with a black line (Fig. 2a). The areas between 20–40%, 40–60%, and 60–80% were referred to as small, medium, and large, respectively. The experimenter used these "ranges" as a verbal command to provide a guidance regarding the expected magnitude of force to be provided by the subjects. The instruction provided to subjects was 'to produce each force pulse as fast as possible and to relax immediately without paying attention to accuracy.' In each testing session, subjects provided a total of approximately 120 force pulses in four separate trials. Each trial lasted 60 s and included around 30 pulses (pulses were separated by approximately 2 s). Pulses were instructed to be performed as groups of five pulses at each of three ranges, referred to as "small," "medium," and "large" in a balanced order. At least one familiarization trial was completed before each tested muscle group. The entire experiment took around 1 h to complete.

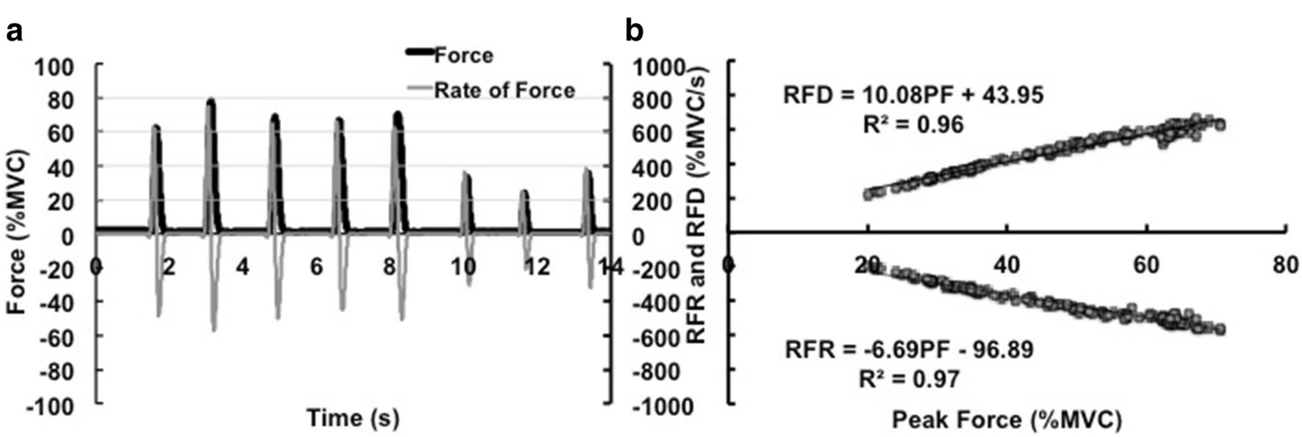


**Fig. 2** **a** An original force (%MVC)—time (s) recording obtained from rapid isometric force pulses (black line) and its time derivative (%MVC/s; grey line). **b** The regression line drawn to the relationship between peak RFD—peak force and peak RFR—peak force. The slopes of the regression lines represent RFD-SF (upper part) and RFR-SF (lower part)

## Data acquisition and analysis

The signals from the force transducers were sampled at 200 Hz using a 16-bit, 250kS/s (for GF and EE) and a 16-bit 500kS/s (for KE) analog-to-digital converters (NI-6224 and NI-6314, National Instruments Corp., Austin, Texas, USA). Both data acquisition and analysis were performed on custom-made LabView routines (National Instruments Corp., Austin, Texas, USA). The force data was filtered with a fourth-order zero-lag low pass filter with a cut off frequency of 50 Hz. The time derivative of the force curve was then calculated and filtered with a fourth-order zero-lag low pass filter with a cut off frequency of 5 Hz and plotted together with the recorded force curve (Djordjevic and Uygur 2017). Two cursors were automatically placed on the time derivative curve corresponding to peak RFD and peak RFR. Another cursor was attached to force curve and depicted the peak force. For every pulse recorded the magnitudes and positions of peak force, peak RFD, and peak RFR were recorded.

To find the initiation and termination of the force pulses, the time derivatives of the force curves were calculated and then filtered with a fourth-order zero-lag filter with a cut off frequency of 10 Hz. This cut off frequency was selected during pilot testing since it provided the initiation and termination points that were almost identical to those detected manually. The initiation and termination of force pulse was automatically depicted on the force curve as the point where the derivative of the force reached 10% of its peak values (Park and Stelmach 2007). The total pulse time was calculated as the time difference between the termination and initiation of force pulse and pulses that lasted more than the mean plus two standard deviations of the duration of all pulses were excluded from analysis.

The regression parameters obtained from the relationships between the peak force (PF) and the corresponding peak RFD and peak RFR were used as dependent variables of quick force generation and force relaxation, respectively. The slopes of these relationships, i.e., RFD-SF and RFR-SF, quantified the magnitude of the ability to scale RFD and RFR with the magnitude of force produced (Fig. 2b). The $R^2$s obtained from the same regressions revealed the consistency of scaling of rate of force development and relaxation with peak force (Bellumori et al. 2011). Absolute values of RFR-SFs were used in the statistical analysis. Similar to previous research (Casartelli et al. 2014; Bellumori et al. 2017; Djordjevic and Uygur 2017), we excluded y-intercepts of the regression lines from our discussion since they were shown to be negligible.

## Statistics

We used SPSS (version 24, IBM SPSS Statistics, Armonk, NY) for the statistical analysis. For each of the selected variable, repeated measures (RM) analysis of variance (ANOVA) was used to 1-) test the differences between sessions and muscles groups, 2-) test the differences between development-relaxation and muscles using the data collected in the first session, and 3-) test the differences in MVC among the tested muscles obtained in the first session. Post hoc tests with Bonferroni corrections were applied for multiple comparisons. The data were Greenhouse-Geisser corrected if Mauchly's test of sphericity was significant. As $R^2$s were not normally distributed, values were Z-transformed in statistical analyses and presented as median values in Table 1 and Fig. 3. For each muscle groups tested, between session reliability of both RFR-SF and RFD-SF were assessed using intraclass correlation coefficient ($ICC_{3,1}$) as computed from all the pulses recorded in each session. ICC values between 0.5 and 0.75 indicate moderate to good reliability, while ICC values > 0.75 suggest excellent reliability (Portney and Watkins 2008). As a measure of absolute reliability, we calculated the coefficient of variation (CV) as an estimate

**Table 1** Maximum force and the regression parameters of the force-rate of force development and force-rate of force relaxation relationships for each muscle in each session

| | Grip force | Elbow extensors | Knee extensors |
|---|---|---|---|
| Max force (N/kg) | | | |
| Session 1 | 2.07 (0.35)$^c$ | 2.53 (0.30)$^b$ | 8.10 (2.02)$^a$ |
| Session 2 | 2.15 (0.49) | 2.70 (0.47) | 8.79 (2.01) |
| RFD-SF (1/s) | | | |
| Session 1 | 9.29 (1.05)$^b$ | 10.75 (0.87)$^a$ | 9.66 (0.89)$^b$ |
| Session 2 | 9.28 (1.03) | 10.40 (1.27) | 9.59 (1.01) |
| $R^2_{RFD}$ | | | |
| Session 1 | 0.98 (0.93–1.00) | 0.96 (0.93–0.99) | 0.97 (0.89–0.99) |
| Session 2 | 0.98 (0.94–1.00) | 0.97 (0.93–1.00) | 0.97 (0.91–1.00) |
| $Intercept_{RFD}$ (%MVC/s) | | | |
| Session 1 | 52.72 (23.72) | 42.08 (30.85) | 35.82 (22.86) |
| Session 2 | 52.78 (31.56) | 47.29 (42.45) | 35.80 (27.66) |
| RFR-SF (1/s) | | | |
| Session 1 | 8.22 (0.76)$^a$ | 7.64 (0.92)$^a$ | 6.01 (1.75)$^b$ |
| Session 2 | 8.30 (0.90) | 7.63 (1.04) | 6.38 (1.40) |
| $R^2_{RFR}$ | | | |
| Session 1 | 0.97 (0.92–0.99)$^a$ | 0.90 (0.80–0.94)$^b$ | 0.79 (0.66–0.99)$^b$ |
| Session 2 | 0.97 (0.93–0.99) | 0.92 (0.85–0.96) | 0.84 (0.70–0.92) |
| $Intercept_{RFR}$ (%MVC/s) | | | |
| Session 1 | 38.78 (21.43) | 22.58 (17.59) | 58.53 (43.69) |
| Session 2 | 33.53 (28.71) | 28.16 (27.79) | 37.75 (44.84) |

Mean (SD); *RFD-SF* Rate of force development scaling factor, *RFR-SF* rate of force relaxation scaling factor, $R^2$ median (range) values of the $R^2$. $a > b > c$.

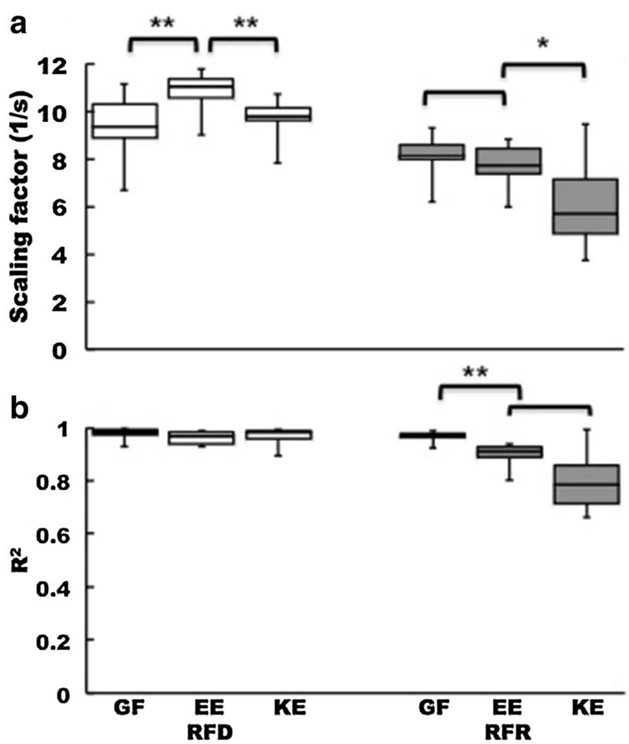


**Fig. 3** The regression parameters obtained from the relationship between peak force and corresponding rate of force development (left panel) and relaxation (right panel) across the tested muscles **a** scaling factors **b** $R^2$'s. Box plots represent 25th–75th percentile of the distribution, middle black line represents median, and whiskers represent minimum and maximum values. **$p<0.01$; *$p<0.05$

of the mean within subject reliability (CV = 100 x standard deviation/mean). Similar to previous research, we considered CV < 15% as good reliability (Staehli et al. 2010). We also calculated standard error of measurement (SEM) as the standard deviation of all test–retest scores x square root of (1-ICC). Pearson correlation coefficients were used to determine the relationships among the tested RFR-SFs and RFD-SFs from the three different muscle groups.

## Results

### Comparison between muscles and sessions

Two-way (three muscles and two sessions) RM ANOVAs performed on the selected parameters obtained from the relationship between PF and RFD and PF and RFR, revealed that there was neither significant session*muscle interaction nor the main effect of session on the selected variables ($p>0.05$). Therefore, with the exception of reliability analysis, we reported and conducted the further analysis only on the data that was recorded during the first session. A one-way RM ANOVA performed on the MVCs obtained from the selected muscle groups revealed significant differences ($F=196.13$, $p<0.001$); indicating that the maximal force capacities of KE was higher than both EE and GF ($p<0.001$) while EE was higher than GF ($p<0.01$) (Table 1).

### Comparison between RFD- and RFR-SFs and $R^2$s

A two-way (three muscles and two scaling factors) RM ANOVA revealed significant main effects of scaling factors ($F=1017.01$, $p<0.001$) and muscle ($F=17.67$, $p<0.001$), as well as interactions between them ($F=10.93$, $p=0.01$). Bonferroni corrected pairwise comparisons revealed that the RFR-SFs obtained from EE and GF were similar and they were higher than the ones obtained in KE. Regarding force development, RFD-SF obtained from GF and KE was similar and both of them were smaller than those obtained in EE. For all the studied muscle groups, RFD-SF was higher than RFR-SF ($p<0.001$) (Fig. 3a).

Another two-way RM ANOVA performed on Z-transformed $R^2$s revealed significant main effects of development-relaxation ($F=117.62$, $p<0.001$), muscle ($F=6.59$, $p<0.01$), and the interaction between them ($F=11.49$, $p<0.01$). Pairwise comparisons revealed that $R^2$s obtained during relaxation was similar between EE and KE and both were lower than those in GF ($p<0.01$). $R^2$s obtained from the development phase were similar among the tested muscle groups and all of them were higher than the $R^2$s obtained from muscle relaxation ($p<0.001$) (Fig. 3b).

### Muscle and scaling factor correlations

Correlations for RFR-SFs among the tested muscle groups were not high enough to reach a significant level ($p>0.05$). Regarding RFD-SFs, we found the highest correlations between the tested upper extremity muscles groups (GF and EE; $r=0.71$, $p<0.01$) while the correlations between GF–KE and EE–KE were not significant ($p>0.05$). Correlations between RFD-SF and RFR-SF within each muscle group revealed a moderate relationship in GF ($r=0.57$, $p=0.04$) and no relationships in EE and KE (Table 2).

### Reliability

The between session reliability of both RFD-SF and RFR-SF obtained from the studied muscle groups was found to be moderate to excellent (ICCs were between 0.54 and 0.76 for RFR-SF and between 0.66 and 0.86 for RFD-SF), respectively. All of the CVs were found to be less than 15% (Table 3).

**Table 2** Pearson correlation coefficients between the RFD-SF and RFR-SF within and among the tested muscles

| | RFD-SF GF | RFD-SF EE | RFD-SF KE | RFR-SF GF | RFR-SF EE | RFR-SF KE |
|---|---|---|---|---|---|---|
| RFD-SF GF | **1** | | | | | |
| RFD-SF EE | 0.71** | **1** | | | | |
| RFD-SF KE | 0.25 | 0.32 | **1** | | | |
| RFR-SF GF | 0.57* | 0.50 | 0.66* | **1** | | |
| RFR-SF EE | 0.70** | 0.27 | 0.20 | 0.40 | **1** | |
| RFR-SF KE | 0.52 | 0.73** | 0.38 | 0.16 | 0.09 | **1** |

*GF* Grip force, *EE* Elbow extensors, *KE* Knee extensors

**$p < 0.01$; * $p < 0.05$

**Table 3** Intraclass correlation coefficient ($ICC_{3,1}$) with 95% confidence interval (CI), coefficient of variation in percentage (CV%), standard error of the measurement (SEM), and SEM as the percentage of the mean values obtained from the first session (SEM%)

| | ICC $_{(3,1)}$ (95% CI) | CV (%) | SEM | SEM (%) |
|---|---|---|---|---|
| RFD-SF_GF | 0.73 (0.32–0.91) | 4.69 | 0.54 | 5.85 |
| RFD-SF_EE | 0.66 (0.19–0.88) | 4.79 | 0.64 | 5.91 |
| RFD-SF_KE | 0.85 (0.59–0.95) | 2.58 | 0.36 | 3.77 |
| RFR-SF_GF | 0.55 (0.31–0.84) | 5.41 | 0.55 | 6.75 |
| RFR-SF_EE | 0.54 (0.02–0.83) | 6.89 | 0.67 | 8.71 |
| RFR-SF_KE | 0.76 (0.53–0.90) | 12.28 | 0.79 | 13.06 |

## Discussion

Within this study, we aimed to develop a clinically relevant kinetic variable to assess the ability to quickly relax a muscle force after a quick force generation across various submaximal ranges. Similar to the rate of force development scaling factor (RFD-SF), we calculated the rate of force relaxation scaling factor (RFR-SF) as the slope of the relationship between the peak forces and the corresponding peak rates of force relaxation. Our findings indicate that (1) similar to the rate of force development, the rate of force relaxation is scaled with the magnitude of peak force across submaximal ranges and, therefore, RFR-SF can be assessed simultaneously with RFD-SF in brief isometric force production tasks, (2) the differences found across the studied muscle groups and the lack of correlation among them indicate that RFR-SF can be muscle specific, (3) the differences found between RFD-SF and RFR-SF and the lack of correlation between them within each studied muscle group indicate that both variables might reflect different properties of the neuromuscular system, and (4) the reliability RFR-SF across the studied muscle groups is moderate to excellent.

### RFR-SF as a variable for neuromuscular quickness

Previous research has shown that when an individual produces rapid force pulses to varying submaximal force levels, the time to peak forces is kept invariant regardless of the size of the force produced (Freund and Budingen 1978; Van Cutsem et al. 1998; Ghez and Gordon 1987). This mandates a strong modulation of the rates of force development with different magnitudes of force being produced. The robustness of this modulation has been studied through the $R^2$ obtained from the linear relationship that exists between these variables. Our results revealed that the $R^2$s obtained from the linear relationship between rate of force relaxation and peak force were 0.97, 0.90, and 0.79 for the GF, EE, and KE, respectively. Therefore, our results indicate that this kind of rate modulation is also present during muscle relaxation following a quick force production in the studied muscle groups of different strength and functional properties.

All of the tested subjects completed both sessions without any adverse effects and the testing lasted around 15 min for each tested muscle group. Our results also show that the testing protocol used in this study was not associated with fatigue [maximum values obtained before vs. after the testing protocol: GF 2.07 vs. 2.25 (N/kg), EE 2.53 vs. 2.77 (N/kg), and KE 8.10 vs. 8.79 (N/kg)]. Therefore, both RFD-SF and RFR-SF should be considered as feasible variables to quantify the neuromuscular quickness of an individual.

Our results revealed that RFR-SF was mainly different among the tested muscle groups (the differences between muscle groups were 7, 16, and 22%) and there was no correlation among them. While we found significant differences in RFD-SF across the studied muscle groups, compared to those found in RFR-SF, they were relatively smaller (the differences between muscle groups were 4, 10, and 13%). Unlike RFD-SF, which was suggested as a single measure of the neuromuscular system (Bellumori et al. 2011), RFR-SF might be dependent on the tested muscle groups. Therefore, we recommend the future studies to test each muscle group separately as they may have different properties that contribute to RFR-SF.

### RFR-SF and RFD-SF comparison

Within each of the studied muscle groups, the magnitudes of RFD-SF were higher than those of RFR-SF and that there was no relationship between the two scaling factors.

Moreover, while the $R^2$s obtained in both development and relaxation phases of force pulses were high, those pertaining to force development were higher than the $R^2$s reported in relaxation. Altogether, these findings suggest that the neuromuscular factors contributing to RFR-SF and RFD-SF might be different (Andersen and Aagard 2006; Hakkinen et al. 1985).

A high RFD-SF has been mainly attributed to the neuromuscular activation mechanisms (Folland et al. 2014) such as a high initial firing rates and the presence of initial double discharges of the motor units (Klass et al. 2008; Van Cutsem et al. 1998) while fiber type composition might be another contributing factor (Andersen and Aagaard 2006; Gordon et al. 1990; Harridge et al. 1996). In contrast, rate of muscle relaxation is mostly dependent on the intrinsic properties of the muscles. Muscle relaxation occurs when the available calcium is pumped back to the sarcoplasmic reticulum by the sarcoplasmic reticulum $Ca^{+2}$ -ATPase (SERCA) and the rate of muscle relaxation is mainly controlled by the SERCA (Rossi and Dirksen 2006). The SERCA found in fast twitch fibers are faster than those found in slow twitch fibers which leads to the relaxation of fast twitch fibers faster than the slow twitch fibers (Rossi and Dirksen 2006). Therefore, the modulation of relaxation with the magnitude of rapid force produced could be related to the amount of fast twitch fiber recruitment. This could be further supported by the higher RFR-SF observed in the elbow extensors than those found in knee extensors when one considers the higher percentage of fast twitch fibers in triceps brachii (30% fast twitch glycolytic fibers (Srinivasan et al. 2007)) than the same percentage in knee extensors (fast twitch glycolytic fibers in vastus lateralis is 20% and in vastus intermedius is 15% (Edgerton et al. 1975)). While the proportion of fast twitch fibers in the intrinsic hand muscles (55.7%) were found to be higher than the same proportion in extrinsic hand muscles (45.9%) (Hwang et al. 2013), the complexity of the muscular structure contributing to grip force production (Maier and Hepp-Reymond 1995) hinders us to make similar conclusions regarding the high RFR-SF observed in GF.

## Reliability

Previous literature has shown a high within (Haberland and Uygur 2017) and between (Bellumori et al. 2011) session reliability for the RFD-SF. Our results indicate moderate to excellent between session reliability of RFR-SF in all of the tested muscle groups (ICCs were between 0.54 and 0.76 and all CVs' < 13%) which were, in general, lower than those obtained for RFD-SF (ICCs were between 0.66 and 0.85 and all CV's < 5%). Moreover, the stabilities of both RFD-SF and RFR-SF are also supported by the lack of differences between the testing sessions indicating that the performance of brief force pulses was stable in the testing sessions.

We found the lowest relative reliability in EE. Similar to the previous research (Bellumori et al. 2011, 2013), we tested EE in conditions where the standing subjects were required to exert forces isometrically through the extension of their elbows. Unlike the GF and KE protocols, the tested muscle group was not isolated and the compensations from other muscle groups (e.g., postural muscles) could have contributed to the variability of the observed results. Future research should consider testing elbow extensors when subjects are seated with their upper bodies are fixed.

The reliability of RFR-SF in this study represents the values obtained from a relatively homogenous sample, which only included apparently healthy and physically active young adults. Therefore, considering the way the ICCs are calculated [ICC = variability between subjects/(variability between subjects + measurement error) (de Vet et al. 2006)], one can speculate that the reliability of the assessed RFR-SF could be higher in heterogeneous populations such as people with neurological diseases and the elderly. Considering the clinical relevance of the ability to quickly relax a muscle force, we recommend future research to test the reliability of RFR-SF in populations that are known to be heterogeneous in an effort to further define and quantify this variable across all populations.

## Clinical relevance

Activities of daily living (e.g., walking, maintaining posture, and fall prevention) require different submaximal magnitudes of quick contractions of agonist muscles and simultaneous relaxation of the antagonist muscles. Therefore, the reductions in the ability to scale the force generation or relaxation might reduce the movement speed across different magnitudes of movement, which has a high impact on motor function and daily living in clinical populations (Ng et al. 2004; Sayers et al. 2005). For example, one of the most common symptoms of Parkinson's disease that deteriorates overall motor function is rigidity and it was found to be significantly correlated with force relaxation speeds (Robichaud et al. 2005).

Both RFR-SF and RFD-SF may be used in clinical settings as objective tools that could supplement the currently used subjective tools (e.g., Unified Parkinson's Disease Rating Scale and Expanded Disability Status Scale) to evaluate motor function. Moreover, both measures can provide quantitative parameters that can evaluate the effects of pharmacological, therapeutic, and medical interventions on motor function and monitor disease progression in people with neurological diseases. Altogether, we believe that the proposed assessment tool is a simple, quick, cost-effective, and ecologically valid one for the assessment of motor function that needs to be tested in clinical populations. While the importance of the ability to quickly relax muscle contractions in daily function is obvious, there is still a need for future studies that investigate the relationship between the rate of muscle relaxation and motor function in various healthy and clinical populations.

### Limitations

A limitation of our study was the lack of recording of the muscle activity. Therefore, one can speculate that the force reductions after producing quick forces might be due to the activation of the antagonist muscle rather than the relaxation in the agonist muscle. In fact, the previous research that was done on healthy young and older adults showed that in rapid isometric force production tasks both of the agonist and antagonist muscles were silent when the peak force was achieved and remained silent during the force reduction period (Klass et al. 2008; Van Cutsem et al. 1998). Nevertheless, future research should consider recording muscle activity in populations who are known with deficiencies in muscle relaxation.

## Conclusions

Our results indicate that the ability to quickly relax a submaximal muscle contraction can be reliably quantified through the kinetic assessment of rapid isometric force production tasks. One can assume that a slowed rate of force relaxation could reduce the ability to create high muscle torques across the joints and, therefore, might explain the reduction in movement speed commonly observed in people with neurological diseases or those of an advanced age. Therefore, the assessment of this neuromuscular property is crucial in populations whom are known with increased spasticity (e.g., cerebral palsy, stroke) and rigidity (Parkinson's disease). Future research should also be conducted to reveal the functional relevance of RFR-SF in both healthy and neurological populations to quantify the influence of muscle relaxation on functional capacity.

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**Author contributions** MU designed the study. MU, RM, and MA recruited participants. RM and MA collected and analyzed data. MU, RM, and MA interpreted the results of the experiment. MU wrote the first draft and revised the manuscript. RM edited the text.

### Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict of interest.

**Ethical approval** All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

**Informed consent** Informed consent was obtained from all individual participants included in the study.

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