



Short communication

Modelling suppressed muscle activation by means of an exponential sigmoid function: Validation and bounds

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ABSTRACT

The aim of this study was to establish how well a three-parameter sigmoid exponential function, DIFACT, follows experimentally obtained voluntary neural activation-angular velocity profiles and how robust it is to perturbed levels of maximal activation. Six male volunteers (age 26.3 ± 2.73 years) were tested before and after an 8-session, 3-week training protocol. Torque-angular velocity ($T-\omega$) and experimental voluntary neural drive-angular velocity (%VA- ω) datasets, obtained via the interpolated twitch technique, were determined from pre- and post-training testing sessions. Non-linear regression fits of the product of DIFACT and a Hill type tetanic torque function and of the DIFACT function only were performed on the pre- and post-training $T-\omega$ and %VA- ω datasets for three different values of the DIFACT upper bound, $\alpha_{\max}$, 100%, 95% & 90%. The determination coefficients, R^2 , and the RMS of the fits were compared using a two way mixed ANOVA and results showed that there was no significant difference ($p < 0.05$) due to changing $\alpha_{\max}$ values indicating the DIFACT remains robust to changes in maximal activation. Mean R^2 values of 0.95 and 0.96 for pre- and post-training sessions show that the maximal voluntary torque function successfully reproduces the $T-\omega$ raw dataset.

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1. Introduction

In vivo measurements of the maximum voluntary force-velocity relationship show differences to the *in vitro* tetanic profile, with eccentric forces not increasing much above isometric and tending to decline with increasing lengthening velocity (Westing, 1988; Dudley et al., 1990; Weber and Kriellaars, 1997). This difference could be due to a neural, tension-limiting mechanism that reduces maximal neural drive at high levels of muscular tension (Westing et al., 1990; Westing et al., 1991; Pain and Forrester, 2009; Pain et al., 2013). Yeadon et al. (2006) represented the *in vivo* maximum voluntary torque-velocity relationship as a product of a theoretical four parameter Hill-type tetanic torque function, and a three parameter differential activation function (DIFACT). The latter representing the net reduction in neural drive to the muscle with low neural activation at high eccentric velocities to full activation at high concentric velocities. However, the DIFACT function was not explicitly based on measured neural changes and its validity was implicitly assumed through the ability of the combined seven parameter function to reproduce the *in vivo*

torque-velocity profiles. Furthermore, due to its quadratic form, the DIFACT function had multiple equivalent solutions and is difficult to manipulate algebraically. Pain and Forrester (2009) used a sigmoid exponential function to represent the DIFACT function in order to simplify mathematical manipulation when finding solutions for the seven parameter MVC torque function (MVC). Again the function was only implicitly shown to be successful through scaling of voluntary EMG signals (Pain and Forrester, 2009).

Therefore, although now used repeatedly (Lewis et al. 2012; Forrester et al., 2011; Tillin et al., 2012; Pain et al., 2013) in the literature the DIFACT function has yet to be verified in an explicit way. The aims of this study were (i) to establish experimentally how well the DIFACT function follows the *in vivo* voluntary neural activation-angular velocity profiles in a group of subjects; and (ii) to test the robustness of the exponential DIFACT function to perturbed upper levels of maximal activation.

2. Method

Measurements from six male volunteers (age 26.3 ± 2.7 years, body mass 72.9 ± 11.7 kg, height, 172.2 ± 8.4 cm; mean $\pm$ SD) tested before and after eight sessions (over three weeks) of high velocity strength training on an isovelocity dynamometer were used as the raw data to address the aims of this study. They all gave written, informed consent and the study was conducted in accordance with the approval given by Loughborough University Ethical Advisory Committee. In brief, testing followed similar methods to those outlined in Yeadon et al. (2006) for

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the data collection (maximal isometric trials at five knee angles spanning the range of motion and maximal isovelocity trials at 50, 100, 150, 250 & 350°/s) and Forrester et al. (2011) for the data processing and fitting procedures to determine the seven parameter function to describe the *in vivo* torque–velocity profiles. However, there was the addition of a repeat set of measures at all test velocities where supramaximal electrical stimulation of the femoral nerve was carried out using doublet stimulation (Folland and Williams, 2007). The interpolated twitch technique (ITT) was used with these stimulated data to determine the percentage of maximal voluntary neural drive (%VA) during each concentric and eccentric velocity at the optimum joint angle for torque production.

$$\%VA = \left(1 - \frac{\text{superimposed twitch}}{\text{control twitch evoked at rest}}\right) \times 100$$

This resulted in: measured torque–velocity data, level of neural drive, and the determination of the three parameters associated with the DIFACT function. In order to establish: (a) how well the DIFACT function follows the *in vivo* voluntary neural activation–angular velocity profiles and (b) whether different values of the DIFACT upper bound, $\alpha_{\max}$, affect the statistical comparison between pre- and post-training results a non-linear regression fit of the seven parameter MVC torque function was performed to each torque vs. angular velocity ($T-\omega$) dataset. This was done first to the individual subject results and subsequently to the combined datasets, with the DIFACT upper bound, $\alpha_{\max}$, set successively at 100%, 95% and 90%. This range was chosen as %VA has been shown to be as low as around 89% during slow isokinetic concentric contractions of the quadriceps and increase with increasing angular velocity (Babault et al., 2001, 2002; Paillard et al., 2005). The fits for each subject were statistically compared using the extra-sum-of-squares *F*-test (Motulski and Christopoulos, 2004) to establish whether the training intervention had a statistically significant effect on any of the subjects.

The goodness of fit of the resulting maximal voluntary torque–velocity curves was assessed: The values of the determination coefficient, R^2 , and RMS difference scores from each fit were calculated for every $\alpha_{\max}$ value. A mixed two-way ANOVA was used to assess any differences in the R^2 and RMS scores per $\alpha_{\max}$ value both within and between the two testing sessions.

The same process was repeated for fitting the DIFACT function to the %VA values of both testing sessions. The R^2 values obtained from the two fits are indicative of how well the fitted functions reproduce the raw $T-\omega$ and %VA– ω profiles and show whether or not the DIFACT function successfully follows the *in vivo* voluntary neural activation–angular velocity profiles. The degree that the RMS and R^2 values change for different values of $\alpha_{\max}$ is a measure of the robustness of the DIFACT function. In order for the DIFACT function to be robust no significant differences between the results of the fits with the different $\alpha_{\max}$ values should be observed within the pre-training data, or in the post-training data.

The curve fit and statistical analysis was performed using Matlab (The Math-Works Inc., Natick, MA, USA). A statistical level of significance, $p < 0.05$, was used throughout.

3. Results

Applying the extra-sum-of-squares *F*-Test on the seven parameter MVC function fit to the torque–angular velocity dataset, for $\alpha_{\max}=100\%$, showed that 3 out of 6 subjects had a significant ($p < 0.05$) higher torque output post-testing. The same outcome was obtained when the $\alpha_{\max}$ values were set equal to 95% and 90%.

There was no significant difference between the R^2 values of the three fits with different $\alpha_{\max}$ values for both pre- and post-training datasets ($p=0.95$ & $p=0.99$ respectively) for any of the six subjects. The mean R^2 values across all subjects (group mean) were 0.95 for pre-training (range 0.84–0.99) and 0.96 for post-training (range 0.89–0.99). Additionally, there was no significant difference ($p \geq 0.05$) in the group mean R^2 scores between sessions. Similarly,

there was no significant difference between the RMS scores of the three fits with different $\alpha_{\max}$ values for any of the six subjects (Table 1) either pre- or post-training ($p=0.92$ & 0.96, respectively). The RMS score variation was much greater between subjects than any variation due to changing $\alpha_{\max}$ within subjects. Group mean RMS scores were 18 (range 7.6–45.7) and 13.9 (range 5.3–26.7) for pre- and post-training sessions respectively. There was no significant difference ($p \geq 0.05$) in the group mean RMS scores between the two sessions.

When the DIFACT function was fitted on the %VA dataset the R^2 values per testing session were not significantly different ($p \geq 0.05$), however, the post-training group mean R^2 score, 0.68, was significantly ($p < 0.05$) higher than the pre-training value, 0.57. The respective ranges were 0.32–0.84 and 0.32–0.89. Again the R^2 score variation was much greater between subjects than any variation due to changing $\alpha_{\max}$ within subjects. Similarly, there was no significant difference between the RMS scores of the three fits, with different $\alpha_{\max}$ values, to the %VA– ω profiles for either pre- or post-training ($p=0.98$ & 0.63 respectively). The RMS score variation was greater between subjects than any variation due to changing $\alpha_{\max}$ within subjects. The group mean RMS post-training score, 0.09 (range 0.04–0.15) was significantly ($p < 0.05$) lower than the respective pre-training mean RMS score (0.11, range 0.062–0.182). Mean %VA values across eight different isovelocities showed a general rise from mid 60 s to low 90 s but with post training generally being 5% higher (Table 2). Mean $\alpha_{\min}$ was

Table 2

Mean %VA values and standard deviations (SD) pre- and post-training for each angular velocity (deg/s).

Angular velocity	Mean %VA $\pm$ SD	
	Pre training	Post training
–250	67.4 $\pm$ 12.60	68.5 $\pm$ 11.90
–150	63.6 $\pm$ 15.60	72.0 $\pm$ 7.50
–100	64.8 $\pm$ 20.30	69.7 $\pm$ 11.70
–50	67.1 $\pm$ 10.36	76.1 $\pm$ 4.36
0	86.3 $\pm$ 9.15	89.2 $\pm$ 3.49
50	85.5 $\pm$ 5.17	88.7 $\pm$ 3.93
100	88.6 $\pm$ 7.88	94.1 $\pm$ 2.58
150	91.3 $\pm$ 4.24	94.7 $\pm$ 1.33

Table 3

Mean $\alpha_{\min}$ values in % and SD pre- and post-training for each value of $\alpha_{\max}$.

$\alpha_{\max}$ (%)	Mean $\alpha_{\min} \pm$ SD	
	Pre training	Post training
100	62 $\pm$ 0.04	67 $\pm$ 0.05
95	60 $\pm$ 0.02	64 $\pm$ 0.04
90	61 $\pm$ 0.02	63 $\pm$ 0.05

Table 1

RMS differences for the 7-parameter torque function fit to the $T-\omega$ data for $\alpha_{\max}=100\%$, 95%, 90%.

	Pre training			Post training		
	$\alpha_{\max}=100\%$	$\alpha_{\max}=95\%$	$\alpha_{\max}=90\%$	$\alpha_{\max}=100\%$	$\alpha_{\max}=95\%$	$\alpha_{\max}=90\%$
Subject 1	41.2	45.7	45.6	8.8	8.5	8.5
Subject 2	11.2	13.8	11.3	4.7	5.3	5.3
Subject 3	14.5	17.2	14.4	26.6	27.2	26.7
Subject 4	8.0	8.0	8.0	7.0	7.0	7.0
Subject 5	7.6	7.7	12.1	15.1	15.1	15.1
Subject 6	17.5	24.4	16.0	20.5	20.5	20.5

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