JOURNAL OF BIOMECHANICS **48**(4):712-715 26 Feb 2015

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-ω) 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 toque function and of the DIFACT function only were performed on the pre- and post-training T-ω and %VA-ω datasets for three different values of the DIFACT upper bound, α_{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 α_{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-ω raw dataset.

Key words: interpolate twitch, force, velocity, quadriceps

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 & 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.,* 1991; Pain & 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 & 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 & 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.

METHODS

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 ± 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 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 & 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 the DIFACT upper bound, α_{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-ω) dataset. This was done first to the individual subject results and subsequently to the combined datasets, with the DIFACT upper bound, α_{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 (Motulsky & 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 α_{max} value. A mixed two-way ANOVA was used to assess any differences in the R^2 and RMS scores per α_{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-ω 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 α_{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 α_{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 MathWorks Inc., Natick, MA, USA). A statistical level of significance, $p<0.05$, was used throughout.

RESULTS

Applying the extra-sum-of-squares F-Test on the seven parameter MVC function fit to the torque-angular velocity dataset, for α_{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 α_{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 α_{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 to 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 α_{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 α_{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.

Table 1 RMS differences for the 7-parameter torque function fit to the T-ω data for α_{max}= 100%, 95%, 90%,

	Pre training			Post training		
	α_{max}=100 %	α_{max}=95%	α_{max}=90 %	α_{max}=100 %	α_{max}=95%	α_{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

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 α_{max} within subjects. Similarly, there was no significant difference between the RMS scores of the three fits, with different α_{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 α_{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 60s to low 90s but with post training generally being 5% higher (Table 2). Mean α_{min} was similar to the lowest %VA values at around 60% for pre-training and 64% for post training (Table 3)

Table 2 Mean %VA values and standard deviations (SD) pre- and post-training for each angular velocity (deg/sec).

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

Table 3. Mean α_{min} values in % and SD pre- and post-training for each value of α_{max}

α_{max} **(%)**	**Mean α_{min} ± SD**	
	Pre Training	**Post Training**
100	62 ± 0.04	67 ± 0.05
95	60 ± 0.02	64 ± 0.04
90	61 ± 0.02	63 ± 0.05

Figure 1 illustrates how the DIFACT-function obtained from fitting the seven parameter function to the torque-angular velocity dataset of Subjects 2 and 4 follows the raw ITT-angular velocity dataset for the three α_{max} values and how this compares against the DIFACT-function fit to the ITT-angular velocity dataset.

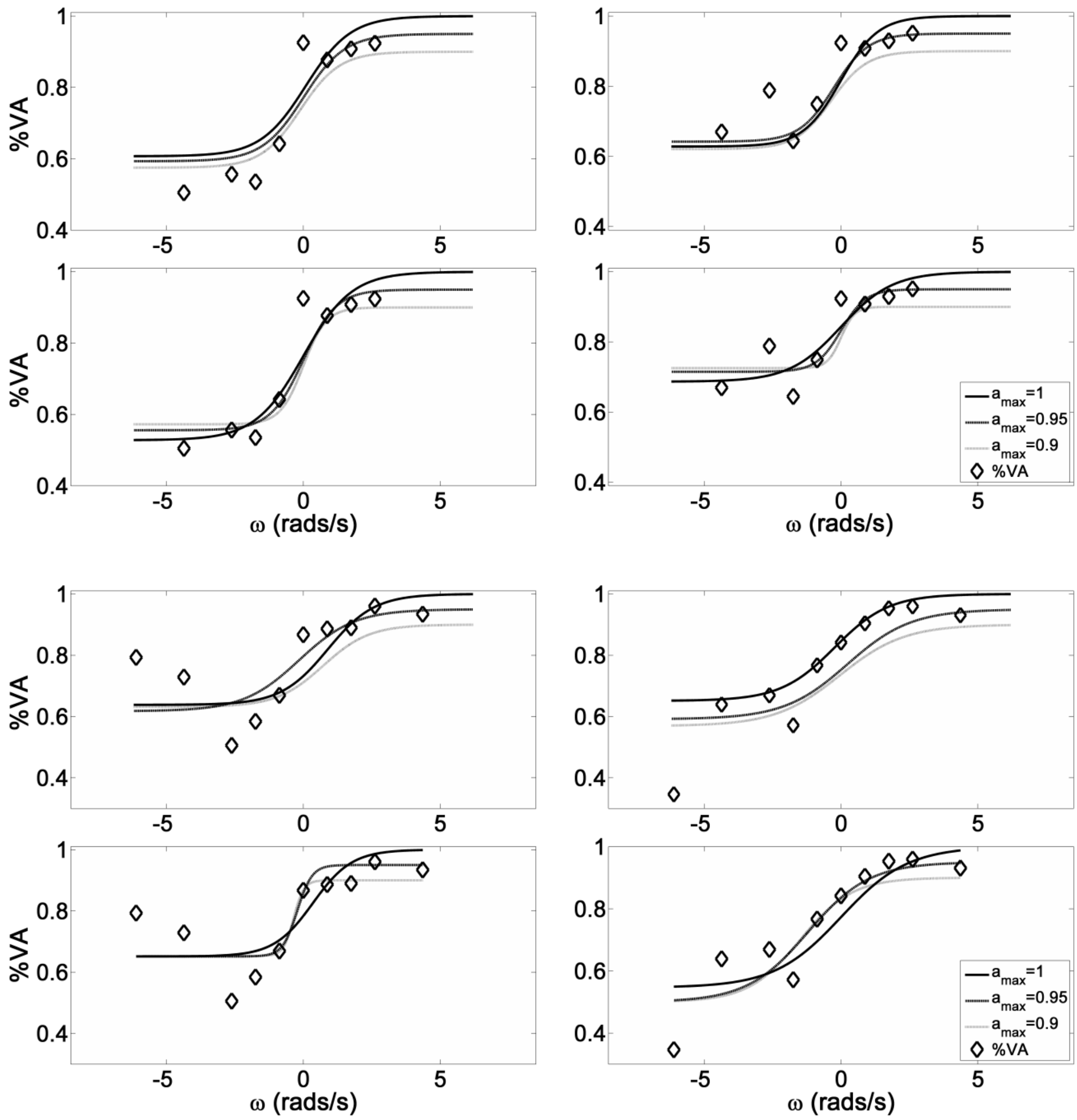

Figure 1 The four graphs show how the DIFACT function compares with the raw %VA-ω data set for α_{max}=100%, 95%, 90% for Subjects 2 (a) and 4 (b). Graphs on the left correspond to the pre-training values and on the right to the post-training ones. The top two graphs, per subject, show the DIFACT function from the seven parameter fit superimposed on the %VA-ω data set. In the bottom two graphs the DIFACT function has been fitted to the %VA-ω data set directly and again plotted against the respective %VA-ω values.

DISCUSSION

The aim of this work was to determine how well the three-parameter exponential differential activation function DIFACT (Pain & Forrester, 2009) reproduces the *in-vivo* T-ω and %VA-ω profiles and whether changing the value of the maximum activation level, α_{max}, in DIFACT (Pain & Forrester, 2009) would affect its robustness. Results show that the MVC torque function reproduces the T-ω raw data set very well irrespective of the α_{max} value. The DIFACT function is also successful in reproducing the raw %VA-ω data set albeit not to the same extent as the torque function. This is, probably, due to the increased variability in the %VA values of some subjects obtained from eccentric contractions, mainly during the pre-training session. A number of factors may have been the cause of the observed variability such as the expectation of noxious stimuli (Shield & Zhou, 2004) or a possible variation between trials in the joint angle where the stimulus was applied (Tillin *et al.* 2012). However, the DIFACT function appears to behave consistently irrespective of the range of %VA values or the presence of outlier points (Figure 1).

In previous studies (Yeadon *et al*., 2006; Pain & Forrester, 2009, Forrester *et al.,* 2011), the maximum activation level of DIFACT, α_{max}, was assumed to be equal to 100%, corresponding to full activation, 100%, of the muscles at high concentric velocities. However, activation deficits of 5-30% have been reported during high concentric contractions (Babault *et al*., 2001, 2002; Paillard *et al*., 2005) in agreement with the results of this study showing that the muscles do not attain full activation. Using α_{max} values between 90% and 95% might be a better representation of the maximum activation of muscles during voluntary efforts. In the current study an α_{max} value of 100% appears to be the appropriate value to use for the post-training as four subjects achieved the lowest RMS scores for that value post-training and there are strong indications of increased neuromuscular activation, due to the training protocol (Table 2). For the pre -training datasets an α_{max} value of 95% seems to be more suitable as the overall activation is lower, suggesting that setting the α_{max} at 100% may be excessive. However, setting α_{max} = 90% is likely too low to account for fast concentric contractions where the muscle activation appears to be enhanced compared to other types of contraction (Tillin *et al.* 2012) and surpassed the values reported here (Table 2). Given this and the robustness of the fitting methods, setting α_{max} to 100% in most cases is likely an assumption that will not introduce any meaningful errors. Indeed, when the mean raw torque outputs at 350°/s are compared against the mean values of the 7-parameter MVC function fits, at 350°/s, with α_{max} set at 100% and 95%, the differences were 3.7% and 1.3% respectively for the pre-training results and 0.9% and 0.8% post-training. Moreover, the mean α_{min} value of 67% compares very well with the mean %VA value of 69% at -250°/s (a velocity where the inhibition would be significant) post-training suggesting the use of a higher α_{max} value for analysing post-training datasets. The higher post-training R^2 values imply an improved fit in line with the expectation of a more consistent activation pattern and activation profile, with respect to angular velocities, post-training.

Overall the mean R^2 values of the DIFACT fit to the %VA-ω pre- and post-training (0.57 v 0.68), the agreement between the α_{min} and %VA values at -250°/s, the qualitative agreement between the fitted DIFACT function and the raw datasets observed in Figure 1 suggest that the neural inhibition (Westing, 1988; Dudley *et al*., 1990; Weber & Kriellaars, 1997) may be represented by means of an S-shaped function such as the DIFACT function. Concluding, it has been shown that the exponential DIFACT function remains robust for various values of the maximum level of activation value, α_{max}, and it represents well the neural inhibition of the knee extensors during fast eccentric and slow concentric contractions.

Conflict of Interest Statement
Neither author has any conflict of interests

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