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Comparing EMG amplitude patterns of responses during dynamic exercise: Polynomial vs log-transformed regression

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The purposes of this study were to determine if (a) the log-transformed model can be applied to dynamic exercise and (b) the slope and *y*-intercept terms can provide additional information above and beyond the polynomial regression analyses. Eleven physically active individuals performed incremental cycle ergometry on a single occasion. Electromyographic electrodes were placed on the three superficial quadriceps muscles to record muscle activation during the exercise test. The patterns of responses for electromyographic amplitude vs power output were analyzed with polynomial and log-transformed regression models. The results of the polynomial regression for the composite data indicated that the best-fit model for the vastus lateralis muscle was linear ($R^2 = 0.648$, $P < 0.0001$), whereas the best-fit model for the rectus femoris ($R^2 = 0.346$, $P = 0.013$) and vastus medialis ($R^2 = 0.764$, $P = 0.020$) muscles was quadratic. One-way repeated measures analyses indicated no significant differences ($P > 0.05$) across the three superficial quadriceps muscles for the slope and *y*-intercept terms. These findings suggest that the log-transformed model may be a more versatile statistical approach to examining neuromuscular responses during dynamic exercise.

Surface electromyography (EMG) is a non-invasive method of examining neuromuscular response during various perturbations such as isometric (Beck et al., 2004a), isokinetic (Beck et al., 2004b, 2006), and dynamic muscle (Malek et al., 2009a) actions with small (Beck et al., 2004a, 2004b) and large (Malek et al., 2006a) muscle groups. The amplitude of the surface EMG signal reflects muscle activation (both motor unit recruitment and firing rate), while the frequency content is determined by the average muscle fiber action potential conduction velocity and shape of the waveform (Basmajian & De Luca, 1985). Indeed, the information provided by the EMG signal has been used to determine the efficacy of rehabilitative training regimens for various populations (Ehrenborg & Archenholtz, 2010; Mazzoleni et al., 2011; Sacco et al., 2012).

Studies have used regression analyzes to describe the relationship between the EMG signal and work for dynamic exercise such as cycle ergometry (Malek et al., 2009b). For example, Shinohara et al. (1997) used linear regression to determine the relationship between EMG amplitude and power output. An advantage of linear regression is that comparison of slopes can be made across subjects or muscle groups. A disadvantage of linear regression, however, may be that it does not provide the best description between the EMG signals vs power output relationship. Polynomial regression is an extension of linear regression by which the slope term is raised to the *n*th order (Schmidt et al., 2013). Two common polynomial regression functions used in describing the EMG vs work relationship are the quadratic and cubic models (Travis et al., 2011). Malek et al. (2006a) used polynomial regression analyses to determine if linear regression was the best-fit model for the patterns of responses for the EMG signal vs power output. The investigators (Malek et al., 2006a) reported that the patterns of responses for EMG amplitude vs power output were best-fit with a linear regression model for 54% of the subjects, whereas the quadratic regression model best-fit the data for the remaining subjects. Similarly, Zuniga et al. (2009) have reported that the patterns of responses for EMG amplitude vs power output were best-fit with a linear model for 70% of their subjects, whereas the quadratic model best-fit the data for the remaining subjects. These results suggest a lack of consistency in describing the patterns of responses for EMG amplitude vs power output when using polynomial regression. Furthermore, a potential limitation of the polynomial regression is that the investigator cannot compare the slopes of the regression line between subjects, gender, and/or muscle groups which may provide additional information related to motor control during incremental exercise.

Recently, Herda et al. (2009) proposed a natural log-transformed model for examining the torque-related patterns of responses for mechanomyographic (MMG) amplitude. Thus, instead of examining the MMG amplitude vs torque relationship, the investigators examined the natural log of this relationship using the following equation:

$$Y = aX^b$$

where a is the "gain factor," because it scales the relationship along the y-axis and b described the non-linearity of the relationship as well as the rate of change in the variables (Herda et al., 2009). Therefore, if $b < 1$ the relationship has plateaued, whereas if $b = 1$ the relationship is linear (Herda et al., 2009). In addition, for values in which $b > 1$ the relationship is described as accelerating upward (Herda et al., 2009). The investigators found that this mathematical model had higher reliability and provided information that could be easily interpreted physiologically (Herda et al., 2009). Taken together, the log-transformed model may provide an alternative statistical model to the polynomial regression for examining motor unit activation strategies.

No studies to date, however, have compared and contrasted the log-transformed model with the polynomial regression model for incremental cycle ergometry. Therefore, the purposes of this study were to determine if (a) the log-transformed model can be applied to dynamic exercise and (b) the a and b terms can provide additional information above and beyond the polynomial regression analyses.

Materials and methods

Experimental design and procedures

Each subject visited the laboratory for a single occasion and had EMG electrodes placed on the superficial quadriceps muscles on the exercised leg. Thereafter, each subject performed an incremental cycle ergometry to voluntary exhaustion.

Subjects

Eleven college aged (mean ± SEM, 19.3 ± 0.5 years) men ($n = 6$) and women ($n = 5$) who maintained a habitual aerobic training regimen were recruited from the university campus student population. All subjects signed an informed consent form and completed a pre-screening health history questionnaire. All procedures were approved by the University Institutional Review Board.

Incremental cycle ergometry

Each subject performed an incremental test to voluntary exhaustion on a calibrated Monark electronically braked cycle ergometer (829E, Country Technology, Inc., Gays Mills, Wisconsin, USA) at a pedal cadence of 70 rev/min. The subjects were also fitted with a Polar Heart Watch system (Polar Electro Inc., Lake Success, New York, USA) to monitor heart rate throughout the test. After a period of stabilization at rest in which the pre-exercise heart rate was stable during a 3–4-min period, the subjects began pedaling at 50 W for 2 min for the warm-up phase. The power output was then increased by 25 W every minute throughout the test. The durations for the exercise tests were between 8 min and 15 min (Buchfuhrer et al., 1983). Rating of perceived exertion (RPE) scale (0–10) with standard instructions was recorded for every workload. Consistent with our previous work, termination of the exercise test was determined if the subject met at least two of the following three criteria: (a) 90% of age-predicted heart rate (220-age), (b) RPE of 8 or higher, and (c) inability to maintain the pedal cadence of 70 rev/min despite strong verbal encouragement (Malek et al., 2009a, 2010; Malek & Coburn, 2011).

EMG measurements

Three separate bipolar (20 mm center-to-center) surface electrode (EL500-6, BIOPAC Systems, Inc., Santa Barbara, California, USA) arrangements were positioned over the longitudinal axes of the vastus lateralis (VL), rectus femoris (RF), and vastus medialis (VM) muscles. The electrodes for the VL were placed over the lateral portion of the muscle at approximately the two-thirds from the head of the greater trochanter and the lateral condyle of the femur (Malek et al., 2006a; Travis et al., 2011). For the RF, the electrodes were placed at 50% the distance between the inguinal crease and the superior border of the patella (Travis et al., 2011). The electrode placement for the VM was 20% of the distance between the medial gap of the knee joint and the anterior superior iliac spine of the pelvis (Zipp, 1982; Travis et al., 2011). The reference electrodes were placed on the iliac crest. The shaved skin at each electrode site was carefully abraded and cleaned with alcohol, and interelectrode impedance was kept below 2000 ohms. The EMG signal from each electrode placement site was amplified (gain: ×1000) using differential amplifiers (EMG 100B, BIOPAC Systems, Inc.).

Signal processing

The raw EMG signals were digitized at 1000 Hz and stored in a personal computer (Dell Inspiron E1705, Dell Inc., Round Rock, Texas, USA) for subsequent analysis. All signal processing was performed using custom programs written with LabVIEW programming software (version 7.1, National Instruments, Austin, Texas, USA). The EMG signals were bandpass filtered (fourth-order Butterworth) at 10–500 Hz. The amplitude (microvolts root mean square, μVrms) value for each stage was calculated for each subject based on the average of the last three completed bursts. The EMG mean power frequency domain was not analyzed as studies have shown that there are no consistent patterns of responses during incremental continuous exercise (Malek et al., 2006a, b; Travis et al., 2011).

Statistical analyses

For each subject, power output and EMG amplitude were normalized as a percentage of the maximum value (%max) which typically occurs toward the termination of the exercise. Polynomial regression analyses were used to determine the patterns of responses for the absolute and normalized (%max) EMG amplitude vs normalized power output among the three superficial quadriceps muscles consistent with our previous work (Malek et al., 2009a; Travis et al., 2011). This approach was used for the composite data as well as on a subject-to-subject basis as initially recommended by Malek et al. (2006a, b). The data were also analyzed using the log-transformed model recommended by Herda et al. (2009). Briefly, the regression model was transformed to a natural log as represented by the equation (Fig. 1):

$$\ln[Y] = b(\ln[X]) + \ln[a] \quad (1)$$

where ln[Y] is the natural log of the EMG amplitude values, ln[X] is the natural log of the power output, b is the slope term, and ln[a] is the natural log of the y-intercept (Herda et al., 2009). In addition, using an antilogarithm function, eqn. 1 is converted to:

$$Y = aX^b \quad (2)$$

where the exponent Y is equal to the predicted EMG amplitude, X is the power output, b is the slope of the log-transformed equation (Herda et al., 2009) (Fig. 1). Therefore, using eqn. 2 values such as the coefficient of determination (R^2), slopes, and y-intercepts were calculated on a subject-by-subject basis.

Separate one-way repeated measures analyses of variance were conducted to determine mean differences between the dependent variables across muscle groups. Statistical significance was set at $P < 0.05$, and the data were analyzed using the Statistical Package for the Social Sciences software (v. 19.0, IBM SPSS, Armonk, New York, USA).

Results

Incremental test

The results of the incremental test are shown in Table 1. In all cases, subjects were unable to maintain the 70 rev/min and indicated an RPE rating of greater than 8.

Polynomial regression analyses

The results of the polynomial regression for the composite data for the absolute EMG amplitude indicated that the best-fit model for the VL muscle was linear ($R^2 = 0.648$, $P < 0.0001$), whereas the best-fit model for the RF ($R^2 = 0.346$, $P = 0.013$) and VM ($R^2 = 0.764$, $P = 0.020$) muscles was quadratic. When the data were analyzed on a subject-by-subject basis, the results indicated that for the majority of participants the best-fit polynomial regression models were either quadratic or cubic across the three superficial quadriceps muscles

Table 1. Outcome parameters from the incremental cycle ergometry test (mean ± SEM)

Parameters	Men	Women
Weight (kg)	73.6 ± 3.1	62.0 ± 1.8
Maximal power output (W)	321 ± 22	245 ± 9
Rating of perceived exertion (0–10)	9.5 ± 0.2	9.8 ± 0.2
Heart rate (% of predicted HR_{max})	91 ± 1	94 ± 1

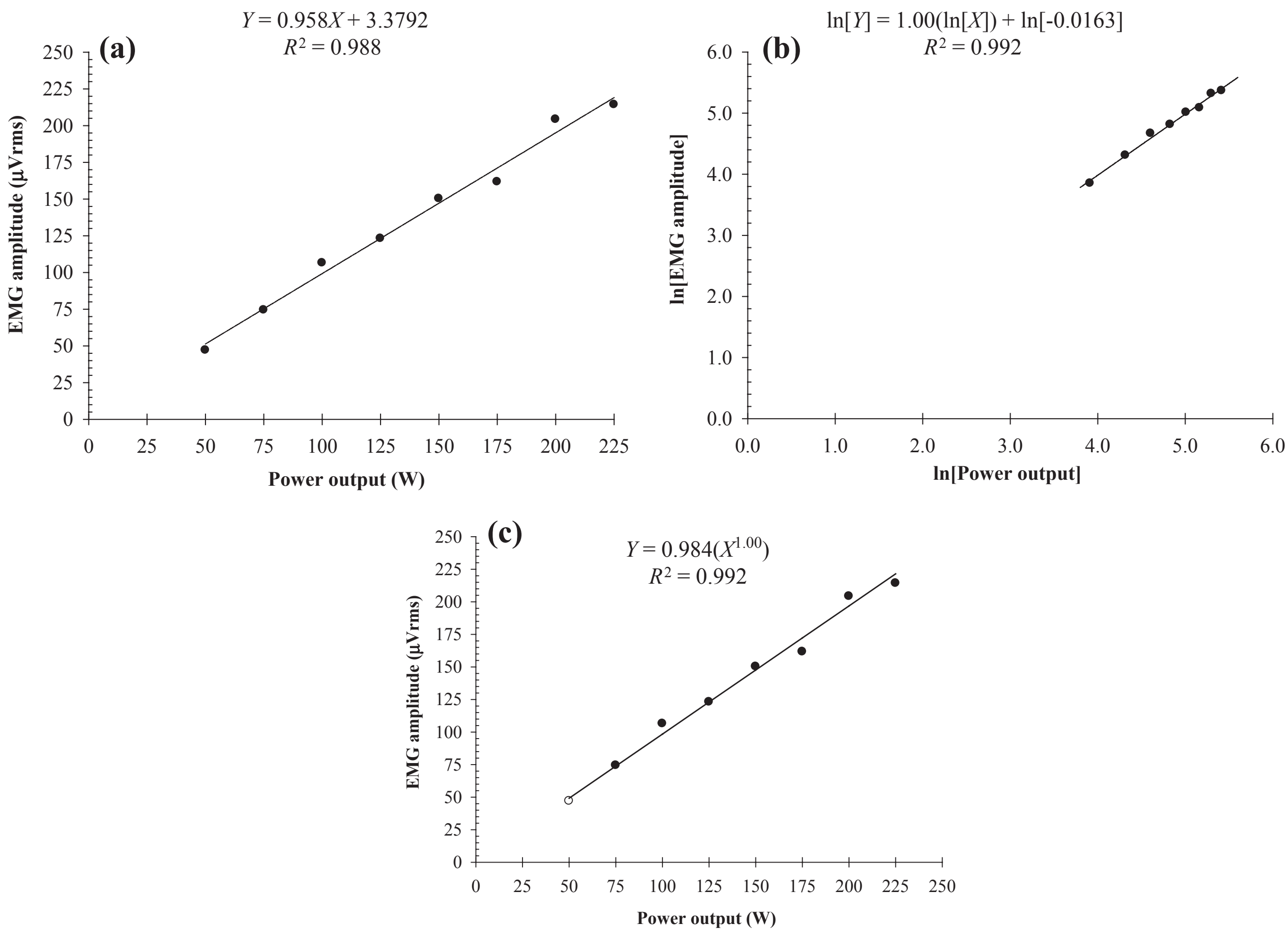

Fig. 1. An example (subject 2, vastus medialis muscle) of the electromyographic (EMG) amplitude (y-axis) vs power output (x-axis) relationship. Panel (a) is the original relationship which was best fit with the linear model. Panel (b) is the log-transformed graph of the relationship. Panel (c) is the original relationship fitted with the exponential equation ($Y = aX^b$), where a = antilog of the y-intercept and b = the slope.

Table 2. Results of the polynomial regression for each muscle on a subject-by-subject basis electromyographic amplitude (polynomial regression)

Subject	Vastus lateralis		Rectus femoris		Vastus medialis	
	Absolute (μVrms)	R^2	Absolute (μVrms)	R^2	Absolute (μVrms)	R^2
1	C	0.989	C	0.992	C	0.988
2	L	0.985	L	0.992	L	0.988
3	Q	0.983	Q	0.952	Q	0.985
4	Q	0.944	Q	0.968	Q	0.949
5	C	0.997	*	*	C	0.994
6	C	0.971	C	0.989	C	0.991
7	L	0.990	*	*	C	0.995
8	C	0.989	C	0.972	C	0.989
9	Q	0.989	Q	0.980	Q	0.991
10	C	0.990	Q	0.943	Q	0.974
11	C	0.989	C	0.981	C	0.986

* indicates that the noise was too high in the signal for analyses.

(Table 3). A similar result was found for the normalized EMG amplitude vs power output.

Log-transformed analyses

As shown in Table 3, for each subject the log-transformed model was used to analyze the patterns of responses and determine the *a* and *b* terms for each muscle. The coefficient of determination (R^2) ranged from 0.788 to 0.994 across the three muscles (Table 3) which was slightly lower than the values derived from the polynomial regression (range 0.943 to 0.995; Table 2). Because the log-transformed model is a method of normalizing the data, this may result in a decreased R^2 (Sokal & Rohlf, 2012). The one-way repeated measures analysis of variance for the *a* term indicated a significant Mauchly's Test of Sphericity ($P < 0.01$) and therefore, the Greenhouse-Geisser correction [$F(1.04,8.35) = 3.48$; $P = 0.10$] revealed no significant mean differences between muscles. For the *b* term, there was a significant Mauchly's Test of Sphericity ($P = 0.026$) and therefore, the Greenhouse-Geisser correction [$F(1.21,9.71) = 4.44$; $P = 0.06$] revealed no significant mean differences between muscles.

Discussion

The principal finding of the current investigation was that the log-transformed model originally proposed by Herda et al. (2009) provided additional information regarding the patterns of responses for EMG amplitude vs power output during cycle ergometry above and beyond that provided from polynomial regression. For example, for non-linear models (quadratic and cubic), it is difficult to statistically compare the *y*-intercept (*a* term) and slope (*b* term) across the three muscles particularly when the patterns of responses differ between subjects. Thus, by using the log-transformed function, we were able to estimate the *a* and *b* terms for each subject for each muscle. As a result, we were able to statistically compare these two terms across the three superficial quadriceps femoris muscles. Therefore, the log-transformed model provides a level of versatility above and beyond polynomial regression.

Studies examining the patterns of responses between the EMG amplitude vs power output typically use polynomial regression to describe the relationship (Malek et al., 2006a, b, 2009b; Travis et al., 2011; Zuniga & Malek, 2013). There are, however, a number of limitations with this approach which may limit interpretation of motor control strategies during incremental exercise. First, it has been shown that the best-fit line from a polynomial regression may be different between participants and across muscles (Malek et al., 2006a, b, 2009a; Travis et al., 2011; Zuniga & Malek, 2013). That is, for some participants the best-fit line may be with the linear model, whereas for others it would be the quadratic model. Furthermore, it has been shown that the result of the polynomial regression for the composite data is not representative of the subject-by-subject result (Malek et al., 2006a, b, 2009b; Travis et al., 2011; Zuniga & Malek, 2013). Second, it is difficult to compare slopes for the patterns of responses which are best-fit with a non-linear model (i.e., quadratic or cubic). Taken together, while the polynomial regression analysis describes the patterns of responses for EMG amplitude vs power output it is limited as to the amount of information it provides regarding motor control strategies. Therefore, the log-transformed model proposed by Herda et al. (2009) may overcome the limitations of the polynomial regression approach.

b term (slope)

The slope of a regression line indicates how much of a change in *Y* is expected for every one-unit increase in *X* (Zar, 1999). In the log-transformed model, the slope provides information regarding the linearity of the relationship between the dependent and independent variables which may be more applicable when analyzing physiological

Table 3. Results of the log-transformed for electromyographic amplitude for each muscle for each subject electromyographic amplitude (log-transformed)

Subject	Vastus lateralis			Rectus femoris			Vastus medialis		
	R^2	*a*	*b* (95% confidence interval)	R^2	*a*	*b* (95% confidence interval)	R^2	*a*	*b* (95% confidence interval)
1	0.937	0.301	1.31 (0.97–1.65)	0.802	0.030	1.59 (0.79–2.37)	0.961	0.745	1.11 (0.88–1.33)
2	0.956	1.290	0.97 (0.76–1.17)	0.994	0.660	0.96 (0.89–1.03)	0.992	0.984	1.00 (0.91–1.09)
3	0.957	0.701	1.08 (0.89–1.27)	0.878	0.024	1.61 (1.12–2.10)	0.954	0.780	1.05 (0.86–1.23)
4	0.905	0.811	1.10 (0.78–1.42)	0.878	0.109	1.29 (0.86–1.72)	0.976	1.092	1.02 (0.88–1.17)
5	0.981	0.966	1.06 (0.96–1.16)	*	*	*	0.975	0.825	1.07 (0.95–1.19)
6	0.887	0.036	1.44 (1.02–1.85)	0.966	0.865	1.19 (1.01–1.37)	0.975	0.639	1.18 (1.03–1.34)
7	0.989	2.718	0.80 (0.72–0.87)	*	*	*	0.947	0.919	1.02 (0.81–1.24)
8	0.952	0.767	1.01 (0.86–1.16)	0.879	0.455	1.02 (0.77–1.27)	0.958	0.774	1.04 (0.90–1.18)
9	0.906	4.711	0.78 (0.56–1.01)	0.788	0.085	1.41 (0.76–2.06)	0.915	3.857	0.81 (0.59–1.03)
10	0.983	0.968	1.07 (0.97–1.17)	0.847	0.346	0.98 (0.68–1.27)	0.985	0.966	1.06 (0.96–1.15)
11	0.956	0.598	1.09 (0.95–1.23)	0.929	0.076	1.32 (1.10–1.53)	0.967	0.575	1.07 (0.95–1.19)

* indicates that the noise was too high in the signal for analyses.

outcomes (Seber & Wild, 1989; Sokal & Rohlf, 2012). Therefore, it has been suggested that when the *b* coefficient is equal to 1 (or 1 is within the 95% confidence interval) the rate of change in *Y* equals the rate of change in *X* (Herda et al., 2009). Alternatively, if the *b* coefficient is not equal 1 (or 1 is not within the 95% confidence interval) the relationship is non-linear (Herda et al., 2009). Consequently, a *b* term with a value less than 1 would be interpreted as a relationship that decreases, whereas a *b* term with a value greater than 1 would be interpreted as a relationship that increases (Herda et al., 2009).

In the current study, we used the log-transformed approach to examine the *b* term for the EMG amplitude vs power output relationship. We found that for non-linear relationships the *b* term was greater than 1. For example, the patterns of responses for subjects #1 and #4 across the three superficial muscles were best-fit with a cubic or quadratic model (Table 2) which corresponded to a *b* term ranging between 1.02 and 1.59 (Table 3). For subject #9, however, the polynomial regression revealed that the best-fit line for all three muscles was quadratic, but the *b* term for the VL and VM muscles were 0.78 and 0.81, respectively. It should be noted that the 95% confidence interval for both of these muscles were slightly greater than 1 (1.01 and 1.03). Furthermore, we found that for subject #7 the *b* term was less than 1 and the 95% confidence interval did not include 1. Therefore, in the present study the results of the log-transformed model were 90% consistent with the polynomial regression. Furthermore, we were able to statistically compare the *b* terms for all three muscles and found no significant mean differences.

a term (*y*-intercept)

In the linear model ($y = bx + a$), the value of *a* indicates where the regression line crosses the *y*-axis (Zar, 1999). For relationships that can be best-fit with a linear model, it is possible to statistically compare the *y*-intercept in cases where the slopes of the regression line are similar to each other (i.e., parallel lines) (Zar, 1999). In the context of examining the relationship between EMG amplitude vs power output, it is rare to have two lines with non-significant slopes and not always the case in which the best-fit model is linear. Furthermore, it is common when using linear regression to have a negative *y*-intercept which may be difficult to interpret from a physiological perspective (Herda et al., 2009). Therefore, alternative statistical approaches are needed.

In the log-transformed model, the antilog of the *a* term in the equation $Y = aX^b$ has been suggested to indicate the "gain factor" which represents either an upward or downward shift in the EMG amplitude vs power output exponential relationship (Herda et al., 2009). Furthermore, the *a* term is always a positive number thus making the interpretation easier. Herda et al. (2009) suggested that the *a* term may be used to identify the influence of various factors such as muscle temperature or skinfold thickness on the neuromuscular response during various perturbations. In the current study, we were able to compare the *a* term estimated from the log-transform model for each subject and each muscle (Table 3). The results indicated that there were no mean differences between the three superficial quadriceps femoris muscles. To our knowledge, this is the first time in which comparisons between the *y*-intercept across muscles were conducted independent of the results from the polynomial regression.

Potential considerations for the log-transformed model

Herda et al. have used the *b* and *a* terms to examine the EMG-force relationship under various perturbations such as the effects of electrode distance from the innervation zone (Herda et al., 2013) and differentiating between individuals categorized on the percentage of their voluntary activation (Herda et al., 2011). For example, Herda et al. (2013) used an eight-channel linear electrode array on the VL muscle and reported that the *b* values closer to the innervation zone were higher than those distal to the innervation zone. For the *a* term, however, the investigators found no significant differences between the eight channels. In another study, the same investigators (Herda et al., 2011) reported differences in peak-to-peak M-wave values between the medial gastrocnemius and soleus muscles. The investigators reported that the larger *a* term observed for the medial gastrocnemius muscle compared with the soleus muscle indicates that the EMG amplitude was higher across the force spectrum (Herda et al., 2011). The authors concluded that the *a* term may be influenced by the anatomical location of the two muscles because the soleus muscle is deep to the medial gastrocnemius muscle (Herda et al., 2011). It should be noted, however, that the above studies did not examine the utility of the log-transformed model during continuous muscle action such as cycle ergometry. Therefore, future studies using the log-transformed approach to examine the EMG-force relationship for dynamic exercise are needed to determine (a) the intersession reliability of this model, (b) whether endurance and/or strength training preferentially influences the *a* and/or *b* terms, and (c) the effects of detraining.

In summary, the findings of the current investigation demonstrated that the log-transform model was applicable to examining the relationship between EMG amplitude vs power output for incremental cycle ergometry for all three superficial quadriceps muscles. In addition, we were able to estimate a slope (*b*) and *y*-intercept (*a*) term for each subject and corresponding muscles.

Perspectives

Examining the EMG amplitude patterns of responses vs power output has typically used polynomial regression to examine this relationship. This approach, however, is limited because comparisons between regression coefficients are difficult to perform. Herda et al. (2009) recently proposed a log-transformed statistical approach. This mathematical model provides a slope and *y*-intercept term for each subject's EMG amplitude vs power output relationship. As a result, statistical comparisons between muscles for each term can be performed. Future studies are needed, however, to determine if various interventions such as endurance training and/or nutritional supplementation can alter the slope and *y*-intercept terms after treatment.

Key words: Exercise physiology, cycle ergometry, muscular fatigue, quadriceps muscles.

References

Basmajian JV, De Luca CJ. Muscles alive, their functions revealed by electromyography. 5th edn. Baltimore: Williams & Wilkins, 1985: 1–200.

Beck TW, Housh TJ, Johnson GO, Cramer JT, Weir JP, Coburn JW, Malek MH. Electromyographic instantaneous amplitude and instantaneous mean power frequency patterns across a range of motion during a concentric isokinetic muscle action of the biceps brachii. J Electromyogr Kinesiol 2006: 16: 531–539.

Beck TW, Housh TJ, Johnson GO, Weir JP, Cramer JT, Coburn JW, Malek MH. Mechanomyographic amplitude and mean power frequency versus torque relationships during isokinetic and isometric muscle actions of the biceps brachii. J Electromyogr Kinesiol 2004a: 14: 555–564.

Beck TW, Housh TJ, Johnson GO, Weir JP, Cramer JT, Coburn JW, Malek MH. Mechanomyographic and electromyographic amplitude and frequency responses during fatiguing isokinetic muscle actions of the biceps brachii. Electromyogr Clin Neurophysiol 2004b: 44: 431–441.

Buchfuhrer MJ, Hansen JE, Robinson TE, Sue DY, Wasserman K, Whipp BJ. Optimizing the exercise protocol for cardiopulmonary assessment. J Appl Physiol 1983: 55: 1558–1564.

Ehrenborg C, Archenholtz B. Is surface EMG biofeedback an effective training method for persons with neck and shoulder complaints after whiplash-associated disorders concerning activities of daily living and pain – a randomized controlled trial. Clin Rehabil 2010: 24: 715–726.

Herda TJ, Walter AA, Costa PB, Ryan ED, Stout JR, Cramer JT. Differences in the log-transformed electromyographic-force relationships of the plantar flexors between high- and moderate-activated subjects. J Electromyogr Kinesiol 2011: 21: 841–846.

Herda TJ, Weir JP, Ryan ED, Walter AA, Costa PB, Hoge KM, Beck TW, Stout JR, Cramer JT. Reliability of absolute versus log-transformed regression models for examining the torque-related patterns of response for mechanomyographic amplitude. J Neurosci Methods 2009: 179: 240–246.

Herda TJ, Zuniga JM, Ryan ED, Camic CL, Bergstrom HC, Smith DB, Weir JP, Cramer JT, Housh TJ. Quantifying the effects of electrode distance from the innervation zone on the electromyographic amplitude versus torque relationships. Physiol Meas 2013: 34: 315–324.

Malek MH, Coburn JW. Mechanomyographic responses are not influenced by the innervation zone for the vastus medialis. Muscle Nerve 2011: 44: 424–431.

Malek MH, Coburn JW, Tedjasaputra V. Comparison of electromyographic responses for the superficial quadriceps muscles: cycle versus knee-extensor ergometry. Muscle Nerve 2009a: 39: 810–818.

Malek MH, Coburn JW, Tedjasaputra V. Comparison of mechanomyographic amplitude and mean power frequency for the rectus femoris muscle: cycle versus knee-extensor ergometry. J Neurosci Methods 2009b: 181: 89–94.

Malek MH, Coburn JW, Weir JP, Beck TW, Housh TJ. The effects of innervation zone on electromyographic amplitude and mean power frequency during incremental cycle ergometry. J Neurosci Methods 2006a: 155: 126–133.

Malek MH, Coburn JW, York R, Ng J, Rana SR. Comparison of mechanomyographic sensors during incremental cycle ergometry for the quadriceps femoris. Muscle Nerve 2010: 42: 394–400.

Malek MH, Housh TJ, Coburn JW, Weir JP, Schmidt RJ, Beck TW. The effects of interelectrode distance on electromyographic amplitude and mean power frequency during incremental cycle ergometry. J Neurosci Methods 2006b: 151: 139–147.

Mazzoleni S, Boldrini E, Laschi C, Carrozza MC, Stampacchia G, Rossi B. Changes on EMG activation in healthy subjects and incomplete SCI patients following a robot-assisted locomotor training. IEEE Int Conf Rehabil Rob [Proc] 2011: 2011: 5975467.

Sacco IC, Sartor CD, Cacciari LP, Onodera AN, Dinato RC, Pantaleao E, Jr, Matias AB, Cezario FG, Tonicelli LM, Martins MC, Yokota M, Marques PE, Costa PH. Effect of a rocker non-heeled shoe on EMG and ground reaction forces during gait without previous training. Gait Posture 2012: 36: 312–315.

Schmidt CO, Ittermann T, Schulz A, Grabe HJ, Baumeister SE. Linear, nonlinear or categorical: how to treat complex associations in regression analyses? Polynomial transformations and fractional polynomials. Int J Public Health 2013: 58: 157–160.

Seber GAF, Wild CJ. Nonlinear regression. New York: Wiley, 1989: 15–20.

Shinohara M, Kouzaki M, Yoshihisa T, Fukunaga T. Mechanomyography of the human quadriceps muscle during incremental cycle ergometry. Eur J Appl Physiol Occup Physiol 1997: 76: 314–319.

Sokal RR, Rohlf FJ. Biometry : the principles and practice of statistics in biological research. Extensively rev. 4th edn. New York: W.H. Freeman, 2012: 15–200.

Travis LA, Arthmire SJ, Baig AM, Goldberg A, Malek MH. Intersession reliability of the EMG signal during incremental cycle ergometry: quadriceps femoris. Muscle Nerve 2011: 44: 937–946.

Zar JH. Biostatistical analysis. 4th edn. Upper Saddle River, NJ: Prentice Hall, 1999.

Zipp P. Recommendations for the standardization of lead positions in surface electromyography. Eur J Appl Physiol 1982: 50: 41–54.

Zuniga JM, Housh TJ, Hendrix CR, Camic CL, Mielke M, Schmidt RJ, Johnson GO. The effects of electrode orientation on electromyographic amplitude and mean power frequency during cycle ergometry. J Neurosci Methods 2009: 184: 256–262.

Zuniga JM, Malek MH. Electromyographic responses of the superficial quadriceps femoris muscles during incremental treadmill running. Muscle Nerve 2013: 48: 938–944.