“All talk no torque”– A novel set of metrics to quantify muscle fatigue through isometric dynamometry in Functional Electrical Stimulation (FES) muscle studies

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Abstract. Functional Electrical Stimulation (FES) activates nerves and muscles that have been ravished and rendered paralysed by disease. As such, it is advantageous to study joint torques that arise due to electrical stimulation of muscle, to measure fatigue in an indirect, minimally-invasive way. Dynamometry is one way in which this can be achieved. In this paper, torque data is presented from an FES experiment on quadriceps, using isometric dynamometry to measure torque. A library of fatigue metrics to quantify these data are put forward. These metrics include: start and end torque peaks, percentage changes in torque over time, and maximum and minimum torque period algorithms (MTPA 1 and 2), and associated torque-time plots. It is illustrated, by example, how this novel library of metrics can model fatigue over time. Furthermore, these methods are critiqued by a qualitative assessment and compared against one another for their utility in modelling fatigue. Linear trendlines with coefficients of correlation ($R^2$) and qualitative descriptions of data are used to achieve this. We find that although arduous, individual peak plots yield the most relevant values upon which fatigue can be assessed. Methods to calculate peaks in data have less of a utility, offset by an order of magnitude of ~$10^1$ in comparison with theoretically expected peak numbers. In light of this, we suggest that future methods would be well-inclined to investigate optimized form of peak analysis.

1. Introduction
The isokinetic dynamometer has been around since the 1800s [1] and has been used extensively in the area of muscle strengthening research. The field of Functional Electrical Stimulation (FES) has benefited greatly from the usage of this apparatus in a research context. Isokinetic dynamometers such as the Biodex [2,3] are used to assess the effects of various electrical stimulation protocols on fatigue as measured through quantification of force or torque. For example, Gorgey & colleagues [3] used a Biodex device to measure torque of knee extensor muscles in a study looking at the differential effects of pulse width on fatigue in FES cycling. While muscle biopsies can be used to measure fatigue in a physiological sense, such as in Martin et al. [4], this is a highly invasive procedure.

Torque-measuring devices such as the Biodex isokinetic dynamometer are less invasive, user-friendly and require minimal setup time. Therefore, they may be used to measure fatigue in a more user friendly fashion, albeit by measuring fatigue indirectly. The participant is seated on a chair, which is aligned to a moment arm connected to the dynamometer. This device is connected to a computer, with software that measures and displays torque produced as a muscle contracts. In isometric testing of quadriceps, the leg moves against a resistance and knee joint torque is measured. To perform isometric
testing, the velocity of the device is set at a rate of zero degrees per second [5]. Therefore, dynamometry may be used to measure how various stimulation sequences can affect muscle responses. In addition, the Biodex is a “gold standard” against which other dynamometry methods such as hand-held systems may be compared against in the context of measuring strength [6], demonstrating its’ utility in the field of muscle biomechanics.

Dynamometry may be used to measure how changing electrical stimulation parameters affects torque produced due to muscle contraction. One such electrical parameter is the duty cycle, which is the parameter describing ON time in relation to OFF time, or total stimulation time [7,8]. Changing the duty cycle for example, has been shown to produce differential decreases in force over time in biceps brachii [9]. The aim of the larger study from which this data set was taken evolved around adapting the work of earlier authors Gentz & Moore [10] in a test subject to look at the differential effects of permuting ON, OFF or ON+OFF time of a 1:3 duty cycle on quadriceps fatigue.

The purpose of this paper is to demonstrate how a novel library of metrics developed can be used to describe fatigue from torque-time data, using a test case from an experiment looking at the effects of duty cycle on fatigue.

2. Methods

2.1. Electrical Stimulation Experiment and Biomechanical Setup

2.1.1. Biomechanical setup. A healthy subject (male, 25-years old, author MT) was used as the test subject for electrical stimulation experiments. He provided informed consent for all experiments. He had no history of neuromuscular pathology that excluded him from participating. The subject sat on an isokinetic dynamometer configured to setup mode where isometric torques could be measured. This machine has a moment arm that attaches to a limb. This allows torques to be measured around joints when muscles contract. Therefore, this experiment sought to measure knee joint torque when the quadriceps (thigh) contracted due to electrical stimulation. Upon calibration, the moment arm of the Biodex was set at an angle of 60 degrees knee joint flexion, relative to the horizontal. The subject was set up on the dynamometer such the lateral condyle of the right femur was directly in line with the pivot point (i.e. axis of rotation) of the moment arm, similar to other dynamometry studies [11-13]. The leg was strapped into the machine so the muscle contracted isometrically, without changing length.

2.1.2. Electrical stimulation protocol. There were 22 total sessions of electrical stimulation completed, (3 × 1:3 (baseline), 3 × 2:3, 3 × 3:3, 3 × 1:6, 3 × 1:9, 1 × 1:3 (test), 3 × 2:6, 3 × 3:9). Electrical stimulation was delivered using a hand-held Med4 (OttoBock Healthcare Products Austria GmBH, Vienna, Austria, TGA approved) stimulator, and applying electrodes on the quadriceps femoris. Manual programming of the device was performed to make programs for different duty cycles. All programs were identical except for the duty cycle used to deliver stimulation. Each program was set to a protocol of frequency 30 Hz, pulse width 300 μs, with a 1-s ramp-up and 1-s ramp-down, at the voltage defined by factory settings of the stimulator. This protocol was an adapted form of Gentz & Moore [10]. Current amplitude was manually set at the beginning of each exercise, and was set at 45 mA on a basis of preliminary findings. For most experiments (except 1:3), stimulation was delivered at 1:3 for a 5-min warmup, then the test duty cycle for 20-min. Some trial runs were also performed prior to the actual experiment, for the purposes of optimisation. All permutations were performed on three separate occasions (runs 1,2,3). This with done with at least two days of rest in between trials, similar to Kesar & colleagues [14]. For the purposes of this paper, torque data from the 2:3 [2-s ON, 3-s OFF] duty cycle runs are discussed only. Further, only uncorrected data are presented for the purposes of discussing the data analysis procedures.

2.2. Data Analysis Procedures and Metrics
2.2.1. Metric conceptualization. The Biodex dynamometer produced datasets of time, torque and angle throughout the duration of stimulation. A list of metrics were developed from the literature, supplemented with other metrics to quantify these data (table 1). During preliminary analysis, there were several metrics added to this library in collaboration with members of the research team. However, only a subset of this comprehensive list were used in the final analysis, and these are presented. In addition, some were conceptualised post-hoc. In the context of this experiment, torque waveforms may be considered to be divided up into two distinct time periods: warm-up (Wp), and exercise (Ex), as generated from the two periods of stimulation. The overall exercise is a combination of these two periods. The term “run” (table 1) refers to repeats of the same duty cycle, however in this paper only run 1 of the 2:3 condition is discussed.

2.2.2 Data processing using metric library. The pertinent metrics applied on the torque time data are listed in table 1. These metrics and plots were produced once the data is imported into MS Excel. The fatigue metric used in this study was the strength decrement index modified (SDIM) (section A, table 1). This calculated a percentage decrease in torque by comparing averages of first and last three peaks (section B, table 2). In addition, an expected peak number was calculated that was the number of peaks

Table 1. Torque peak metrics and plots used in this study and computational procedures.

| A. Fatigue Metrics: Metrics taken or derived from literature. |
|---------------------------------------------------------------|
| • Strength decrement indices modified [SDIM]: The decrease in torque over time during warm-up, exercise and overall stimulation. SDIM (Wp-Wp), SDIM (Ex-Ex) & SDIM (Wp-Ex) are computed by calculating FST and APL averages and comparing percentage decreases. Index adapted from Matsunaga et al. [15], who cite Clarke & colleagues [16]; and also from Hartkopp et al. [17]. |

| B. Peak Metrics: Metrics to describe torque peaks. |
|---------------------------------------------------|
| • Individual peaks [Z, F, S, T, A, P & L]: Individual peak values. Z – zeroth peak, F – first peak, S – second peak, T – third peak, A – antepenultimate peak, P – penultimate peak, L – last peak. Z peak is that stimulation peak caused when the current is increased manually prior to the commencement of automated stimulation as manually set. F, S, T appear at start, A, P, L appear at end of a given region of the waveform. |
| • Compound peak values [FST and APL]: Averages of first and last three peaks [excluding Z peak]. |
| • Expected peak number [EPN]: The expected number of peaks in a torque-time dataset based on the number of repeated units of stimulation [period] provided. The period is the sum of the ON, OFF and ramp-up (RU) and ramp-down (RD) times. Calculated by dividing the stimulation time by the period. The EPN may be compared with other maxima calculations, to test how accurate these are in peak detection. |
| • Overall torque metrics [Maximum torque, minimum torque, range, average, median]: Basic features of the torque-time waveform once it has been adjusted about the x- and y- axes. |

| C. Angle Metrics: Metrics to describe angle-time data. |
|-------------------------------------------------------|
| • Overall angle metrics [Maximum angle, minimum angle, angle variation (AV), average, median]: Similar computation to overall torque metrics. |

| D. Derived Torque Plots: Plots generated by applying different manipulations to torque-time data. |
|--------------------------------------------------------|
| • Raw plot: Plot of torque-time waveform as generated by machine. |
| • Processed plot: Waveform shifted such that time zero is when the stimulation begins. Removal of noise either side. |
| • Peak plots: Individual torque peaks. |
| • Maxima and minima plots: Plots derived by applying maxima or minima algorithms to torque data. An exclusion value (EV) was chosen such that peaks above were used for maxima, and peaks below for minima. |
| • Averaged plots: Plots generating by averaging data over 1-s, one-half-period, one-period and two-periods respectively. |
| • Maximum and minimum torque period algorithms [MTPA 1 and MTPA 2]: These plots show maximum and minimum torques occurring in the period surrounding a torque value. The algorithm looks one half-period in front and behind a torque point, then the maximum is displayed. |
| • Peak torque every 5 min and 1 min: The maximum torque occurring every 5- or 1-min [relative to the half-period in front or behind a data point at t = 5 and t = 1 min, respectively]. Generated from MTPA 1 and MTPA 2 plots. Adapted from Formsek [18]. |
expected based on the stimulation applied to the muscle. This value was compared to the number of maxima calculated (section D, table 1) to describe differences in peak counts and those expected. Further, overall torque (section B) and angle (section C) metrics were also computed to describe basic characteristics of the waveform. Following computation of metrics, a global correction factor (GCF) was applied to account for the torque of gravity. These data are not discussed in this paper, as uncorrected data are used for illustrative purposes of how the library can be used in application.

In addition to metrics, plots were generated to give a visual representation of torque data over time (section D, table 1). Raw and processed plots showed the basic features of the waveform over time, whereas peak plots were used to see peaks at the start and end of regions of interest. Maxima and minima, averaged, MTPA and peak torques were also generated in an attempt to describe how torque peaks decrease over time. Computational plots were generated in MS Excel, and methods described in section D of table 1.

3. Results

3.1. Waveform processing

Raw data [time, torque, angle] were obtained in the .LVM format from the Biodex, and imported into MS Excel as .XLSX files. Data were truncated to remove “noise” either side caused by setting up of the leg in the dynamometer. The full waveform for the 2:3 (run 1) is shown in figure 1, with raw waveform (top) and processed waveform (bottom). There are two distinct time periods of the exercise, the 5-minute warm-up (Wp) [1:3], and 20-minute exercise (Ex) [2:3]. Either side of the raw waveform (figure 1, top) are two types of noise. Prior to the beginning of Wp, there is a lower baseline, corresponding to the torque reading before the leg was loaded onto the machine. Then, the baseline changes when the leg is loaded (indicated by the second patch of varying signal, diamond in figure 1 top). The baseline changed due to the leg exerting a torque on the moment arm of the dynamometer, positioned at an angle of 60 degrees flexion. As can be seen on the far right of the waveform (square, figure 1), there is a return to a baseline that is similar to before the experiment was commenced (before diamond, figure 1).

Figure 1. The full waveform for 2:3 (run 1). The torque due to gravity may be seen after the exercise period (square). There are two periods of torque production, warm-up (Wp) and exercise (Ex). These are separated by a short time gap corresponding to when stimulation was changed (circles).

The raw signal was then processed by performing baseline adjustment and shifting such that the zero time point corresponded to start of stimulation (figure 1, bottom). This provided a more clear representation of the generated torque waveform during the period of electrical stimulation. Pre-experimental noise was eliminated, and the torque waveform during the defined periods of Wp and Ex may be seen more explicitly. The direction of torque peaks were initially downward, with a negative
sign convention (figure 1, top). They were changed to positive by multiplying the entire torque series by -1, and are easier to manually inspect (figure 1, bottom). Also, initially the baseline of the torque waveform during stimulation was raised above zero (figure 1, top). The processed waveform was adjusted such that peaks are zeroed about the baseline (by adding 13 Nm to every torque value). Accurate values of torque peaks could then be read from the signal (figure 1, bottom).

3.2. Fatigue and peak metrics
Adjustment of waveforms permitted calculation of fatigue metrics over time. The maximum torque for the 2:3 torque waveform was found to be 36.14 Nm, while the minimum torque was a value of -6.16 Nm [torque range, 42.30 Nm]. The average and median torques were 6.99 Nm & 0.42 Nm, respectively. Peak plots (figure 2) were used to derive fatigue metrics over time by using the magnitude of first and last peaks. Individual peak values for the warm-up period were found to be: 31.77, 30.02, 27.98 & 30.89 Nm [Z,F,S,T peaks], and: 29.55, 28.87 & 29.23 Nm [A,P,L peaks]. The compound peak values for Wp were found to be 29.63 Nm [FST(Wp)], and 29.22 Nm [APL(Wp)]. For the exercise period, peak metrics were: 34.30, 34.78, 34.10, 34.19 Nm [Z,F,S,T peaks], and: 21.54, 20.37, 29.09 Nm [A,P,L peaks]. The compound peak values for Ex were found to be 34.36 Nm [FST(Ex)], and 23.67 Nm [APL(Ex)]. These compound peak values were then used to calculate percentage decreases in torque over the periods of warm-up, exercise and total stimulation (warm-up+exercise). Corresponding strength decrement indices modified were: 1.39 Nm [SDIM(Wp-Wp)], 31.11 Nm [SDIM(Ex-Ex)], and 20.13 Nm [SDIM(Wp-Ex)].

Figure 2. The first and last peaks for 2:3 (run 1).

3.3. Peak approximation – extrema plots
The maxima and minima (extrema) plots were used generated to approximate torque peaks and the baseline respectively. Linear trendlines were superimposed across all plots to assess the degree of appropriateness of a linear fit. The maxima and minima plots (figure 3) had coefficient of correlations of \( R^2 = 0.414 \), and \( R^2 = 0.115 \). Maxima plots were used to compare peaks with those expected by theory. The expected peak number (EPN) for the 2:3 condition was found by dividing the total time of stimulation by the period [2-s ON + 3-s OFF + 1-s ramp up + 1-s ramp down = 7-s], each repetitive unit of stimulation. This was found for the warm-up at 1:3 and exercise at 2:3. The EPN(Wp) was 50 peaks, while the EPN(Ex) was 171.43 peaks. Hence, the total EPN of the entire stimulation period was found to be 50 + 171.43 = 221.43 peaks. The number of maxima computed from the maxima algorithm was found to be 2080, by use of the function COUNT in Excel. Therefore, there was an
approximate difference of one order of magnitude between peaks expected and peaks calculated by the maxima analysis in Excel (figure 3).

![Figure 3. Maxima and minima plots. For maxima, Wp and Ex may be seen as two distinct data sets separated by a gap in stimulation.](image)

3.4. Further peak approximation – MTPAs and peak torque every 5- and 1-minute
Following maxima and minima analysis of torque data, maximum and minimum torque period algorithms (MTPA 1 and MTPA 2) were generated (figure 4). Figure 4 depicts the MTPA 1 and MTPA 2 for all 3 runs of the 2:3 duty cycle experiment. For the run 1 data, MTPA 1 had an $R^2 = 0.216$ (figure 4, top), and MTPA 2 had an $R^2 = 0.049$ (figure 4, bottom). Also computed from these algorithms were maximum torque every 5-min [data not presented] and 1-min. Similar to figure 4, runs 2 and 3 are plotted alongside run 1. The peak torque for the 1-min data had $R^2 = 0.507$ (figure 5).

![Figure 4. MTPA plots. Depicted is the MTPA 1, which was used to approximate peaks, and the MTPA 2 which was used to approximate the baseline. $R^2$ and trendline shown for run 1 only.](image)
3.5. *Averaged plots*

Averaged plots were also found in attempt to reduce torque peak data to plots that could be compared between and across experimental conditions. For the averaged plots, the coefficients of linear fit were: $R^2 = 0.002$ (1-s), $R^2 = 0.005$ (3.5-s), $R^2 = 0.034$ (7-s), and $R^2 = 0.045$ (14-s). Averages over 1-s and two periods (14-s) are shown in figure 6. As may be seen, the 1-s averaging (left) has less of a linear approximation to peaks than the two-period average (right).

3.6. *Angle variation.*

For the variation in dynamometer angle over time (figure 6), the metrics similar to torque metrics (section C, table 1) were also computed. The maximum angle was 60.348 degrees, minimum angle 57.041 degrees, with an angle variation (i.e., range) of 3.307 degrees. The average angle was 58.737 degrees, and median angle 58.740 degrees. Hence, the “accuracy” (defined as the range as a percentage of 60) was a value of $[3.307/60.000]*100 = 5.512\%$.

![Figure 5](image_url)

**Figure 5.** Peak torque plots. Shown is the peak torque in the period of the data point every 1-min. 5-min was also computed, 1-min shown only for illustrative purposes.

![Figure 6](image_url)

**Figure 6.** Averaged plots. Shown are plots with data averaged over two time periods: 1-s (100), and two periods 14-s (1400). Plots were also generated for one half-period 3.5-s (350), one period 7-s (700) [data not shown].

![Figure 7](image_url)

**Figure 7.** Angle variation plot. There was a range of variation of 5.512% of the angle.
3.7 Critique of data plot procedures.

In addition to the quantitative metrics derived from plots, a qualitative description of data analysis procedures was made by the author MT (table 1). A qualitative description of the relative ease of computation of the various plots (table 2) shows how the use of Excel is associated with different degrees of ease, or tedium in calculating various representations of torque (or angle)/time data. The raw waveform had the quickest relative time required to generate a graph, as simple importation and plotting of the data was required to achieve the desired result. The full angle plot was similar, but required an exact awareness of the time zero of Wp in which to commence the recording (and hence plot the waveform). Extrema and MTPA plots took longer to derive as the full waveform had to be plotted first (i.e., start of Wp and end of Ex had to be identified). Then, the data were operated on by relevant formulae to yield these representations of the torque waveform. The individual (first four, last three) plots were by far the most time consuming as iterations of manually selecting the torque/time data where these had to be performed, sometimes multiple times, to obtain the data in the zone of interest. Similar results are also suggested for the “manipulation” parameter (column 2, table 2).

In terms of usefulness, the individual peak plots were the most useful as values could be read from them and fatigue metrics could be derived as a result (e.g., SDIMs). Perhaps the least useful were the minima and MTPA2 plots, as due to the high sampling rate several local minima not representative of of the baseline were encompassed in the plot with the exclusion value of 10 Nm. The low $R^2$ values of 0.115 (minima), and 0.049 (MTPA2) are suggestive that these plots are not accurate representations of the baseline. Comparability trends across plots follow a similar trend (column 4, table 2).

| Waveform plot       | Comp. time | Manipulation | Usefulness | Comparability |
|---------------------|------------|--------------|------------|---------------|
| Raw waveform        | +++        | +++          | ++         | +             |
| Full waveform       | +++        | +++          | +++        | +             |
| Individual peak plots | ++        | +            | +++        | +++          |
| Maxima plots        | +++        | +            | ++         | +++          |
| Minima plots        | +++        | +            | +          | +++          |
| MTPA 1 plot         | +++        | +            | ++         | ++           |
| MTPA 2 plot         | +++        | +            | +          | ++           |
| Peak torque 5-min 1-min plots | +++    | +.5*        | +++**       | +++          |
| Averaged plots      | +++        | +            | N/A***     | ++           |
| Angle variation plot | +++ .5    | +++          | +++        | ++           |

*Computational time to generate plot. Some of these build off the full waveform, so the times shown are relative to once this data set has been obtained (e.g., maxima, MTPA’s).

How easy or difficult it is to manipulate torque/time (or angle/time) data to produce the desired plot. A similar argument also applies to a).

Is it a meaningful metric in the context of examining torque responses for fatigue?

Is easy to compare plot with plots of other runs?

Have to choose every 5 or 1 min and exclude other data which requires more complex analyses.

Averaging over a few periods is perhaps a more meaningful analysis.

Depends on period (consistent with runs from this duty cycle – other runs, and other duty cycle). The averaged dataset changes greatly depending on time periods over which data is averaged.
4. Discussion
This study has successfully shown how a list of derived fatigue metrics may be employed in an experiment looking at torque/time data from isometric dynamometry. Through creation of a library of metrics, a practical example has been provided of how the library can be applied to analyse a quadriceps’ fatigue when stimulated at a duty cycle of 2:3 under isometric conditions.

Use of this library of fatigue metrics was able to demonstrate some profound torque changes over the 25-minute period chosen. The plots showed clearly fatigue arising, reflected as decreasing torque values from the muscle. Further, individual peak plots were able to show “snapshots” of this trend over time, and supplemented with SDIM and individual peak values provide a basis upon which this data could be compared with other experimental conditions (i.e., duty cycles) for the sake of comparison.

The applications of the proposed metric library are not limited to muscle experiments involving electrical stimulation protocol investigations. Isokinetic dynamometry has been used in other studies, such as that of Thorstensson et al. [19] in their work on the force-velocity correlation in isokinetic contractions of the knee extensor group, using a Cybex II system. Furthermore, isokinetic dynamometry has also been used in sports’ contexts to measure isokinetic muscle properties [20,21], for example, to assess if there is added benefit of kinesio taping in muscle torque production [21]. The metrics we have presented here may be of assistance to these fields and hence is not limited to FES. While we have utilised an isometric dynamometry methodology, the library can be adapted to include variables relevant to isokinetic contractions. For example, in isokinetic experiments, contractions are elicited such that fixed rotational velocity are traversed by a muscle [22]. Furthermore, work performed by Drouin et al. [23], which aimed to characterise the “reliability and validity” of a Biodex System 3 machine examined the variables of position and velocity in addition to torque. Therefore, a future refinement of our metric library could incorporate more isokinetic-specific metrics, to increase its usefulness across a range of experimental designs.

The issue of peak analysis is one problem, which has been studied in other fields such as computational cardiology. As such, future work would be well-inclined to apply similar methods to torque-time data. In our study, identification of peaks was attempted by the derivation of maxima and MTPA plots, in order to characterise torque peaks over time. There have been various attempts to quantify electrocardiogram waveforms for example, through identification of “fiducial points” [24] and differentiating the QRS complex [25]. Perhaps insights from the algorithms in this field may assist in identification of torque peaks of Biodex data. Furthermore, use of computational software such as MATLAB which has been used in similar contexts, such as that of ECG analysis to characterise R peaks [26] may solve the issue of slow computation time experienced in the derivation of some of our metrics (table 2).

The methodology of this work is not without limitations. The qualitative critique of various metric methods demonstrated for example, that although individual peak plots are indeed quite meaningful, their computation time is poor in relation to the other plots. Further, the extrema plots, with an average computational time, yield at best average meaningful data. In terms of experimental design, there were several avenues for optimisation, such as quantification of the exact site to provide optimal stimulation through use of a motor pen [27] and assessing whether to stimulate the femoral nerve or quadriceps directly as they differ in terms of aspects such as comfort [28]. Moreover, the lower limb and torso could be held still during the contraction process [29] to minimise the input of residual torques from other movements of the body. In comparison with other runs, there were marked differences in some metrics for example [data not presented]. Future refinements of both data analysis procedures, precise electrical stimulation and dynamometry set-up would assist in yielding meaningful, comparable results. However, this paper has successfully shown, in light of these limitations, how the library may be implemented in practice on torque-time data series.

5. Conclusions
Here it has been successfully demonstrated how a novel list of parameters can be adopted to model fatigue from a muscle undergoing isometric contractions due to FES. Through using data from the thigh, metrics were applied to torque-time waveforms over a 25-minute period. Individual peak plots
were most useful in showing fatigue over time, but were computationally tedious. Future work would utilize advanced computational methods to increase computation time, and the utility of this proposed library in modelling muscle fatigue. Upon these refinements, this library can be adopted by researchers in the wider field of muscle biomechanics, namely within the scope of rehabilitation engineering and exercise and sports science applications. This will hopefully facilitate in making comparisons of muscle fatigue across different applied stimulus (mechanical or electrical) conditions.

References

[1] Gandevia S C 2001 Physiol Rev 81(4): 1725-1789.
[2] Gregory C M, Dixon W and Bickel C S 2007 Muscle Nerve 35: 504-509.
[3] Gorgey A S, Poarch H J, Dolbow D R, Castillo T and Gater D R 2014 JRRD(9): 1455-1468.
[4] Martin T P, Stein R B, Hoepfner P H and Reid D C 1992 J. Appl. Physiol. 72(4): 1401-1406.
[5] Binder-Macleod S A, Halden E E and Jungles K A 1995 Med. Sci. Sports Exerc. 27(4): 556-565.
[6] Martin H J, Yule V, Syddall H E, Dennison E M, Cooper C, Sayer A A 2006 Gerontology 52: 154-159.
[7] Baker L L, Wederich C L, McNeal D R, Newsam C and Waters R L 2000 NeuroMuscular Electrical Stimulation – A Practical Guide (4th ed) (United States of America: Rancho Los Amigos National Rehabilitation Center).
[8] Carmick J 1997 Pediatr Phys Ther 9(3): 128-136.
[9] Naeem J, Azman A W, Khan S, Mustafah Y M IOP Conf. Series: Materials Science and Engineering, 53: 5th Int. Conf. on Mechatronics, 2-4 July, 2013, Kuala Lumpur, Malaysia.
[10] Gentz L and Moore C 1988 Phys Ther. 68(5): 834.
[11] O’Brien T D, Reeves N D, Baltzopoulos V, Jones D A and Maganaris C N 2009 Eur J Appl Physiol 106: 849-856.
[12] Kubo K, Tsunoda N, Kamehisa H and Fukunaga T 2004 Eur J Appl Physiol 91: 349-352.
[13] Gerrits K H, Maganaris C N, Reeves N D, Sargeant A J, Jones D A and De Haan A 2005 Muscle Nerve 32: 73-80.
[14] Kesar T, Chou L-W and Binder-Macleod S A 2008 J Electromyogr Kinesiol 18: 662-671.
[15] Matsunaga T, Shimada Y and Sato K 1999 Arch Phys Med Rehabil 80: 48-53.
[16] Clarke H H, Shay C T and Mathews D K 1954 Arch Phys Med Rehabil 35: 560-567.
[17] Hartkopp A, Murphy R J L, Mohr T, Kjaer M, Biering-Sorensen F 1998 Arch Phys Med Rehabil 79: 1133-1136.
[18] Formusek C 2005 An Isokinetic Functional Electrical Stimulation Leg Cycle Ergometer for Individuals with Spinal Cord Injury. PhD Thesis, The University of Sydney, Australia.
[19] Thorstensson A, Grimby G and Karlsson J 1976 J Appl Physiol 40(1): 12-16.
[20] Gleeson N P and Mercer T H 1996 Sports Med. 21(1): 18-34.
[21] dos Santos Gloria I P et al. 2017 J Back Musculoskelet Rehabil, Uncorrected proof.
[22] Marchant D C and Greig M 2017 Hum Mov Sci 52: 67-73.
[23] Drouin J M, Valovich-mcLeod T C, Shultz S J, Gansneder B M and Perrin D H 2004 Eur J Appl Physiol 91: 22-29.
[24] Plesnik E, Malgina O, Tasic J F and Zajc M 2012 Med Eng Phys 34: 524-529.
[25] Arzeno N M, Deng Z-D and Soon C-S 2008 IEEE Trans Biomed Eng 55(2): 478-484.
[26] Thulasi Prasad S and Varadarajan S 2013 JRET 2(8): 508-513.
[27] Gobbo M, Maffiuletti N A, Orizio C and Minetto M A 2014 J Neuroeng Rehabil 11: 17.
[28] Bergquist A J, Clair J M, Lagerquist O, Mang C S, Okuma Y and Collins D F 2011 Eur J Appl Physiol, 111: 2409-2426.
[29] Laufer Y, Ries J D, Leininger P M and Alon G 2001 Phys Ther. 81(7): 1307-1316.