

The duty cycle in Functional Electrical Stimulation research. Part II: Duty cycle multiplicity and domain reporting

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Abstract

In part I of this review, we introduced the duty cycle as a fundamental parameter in controlling the effect of electrical stimulation pulse trains on muscle structural and functional properties with special emphasis on fatigue. Following on from a survey of the literature, we discuss here the relative ability of intermittent and continuous stimulation to fatigue muscle. In addition, pertinent literature is explored on a more deeper level, highlighting contentions regarding the duty cycle across studies. In response to literature inconsistencies, we propose frameworks upon which the duty cycle parameter may be specified. We present the idea of domain reporting for the duty cycle, and illustrate with practical examples. In addition we dig further into the literature and present a set of notations that have been used by different researchers to report the duty cycle. We also propose the idea of the duty cycle multiple, which together with domain reporting, will help researchers understand more precisely duty cycles of electrical stimulation. As a case study, we also show how the duty cycle has been looked at by researchers in the context of pressure sore attenuation in patients. Together with part I, it is hoped that the frameworks suggested provide a complete picture of how duty cycle has been discussed across the literature, and gives researchers a more trans-theoretical basis upon which they may report the duty cycle in their studies. This may also lead to a more precise specification of electrical stimulation protocols used in patients.

Key Words: functional electrical stimulation (FES), parameters, duty cycle reporting

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Related to the concept of duty cycle are the terms “continuous” and “intermittent” stimulation. In simplest of terms, continuous stimulation is continuous, and intermittent stimulation has gaps where continuous would not. However, this is very open for interpretations. There is no standard definitions of what constitutes continuity versus intermittency in the muscle international literature. This is an issue that renders comparison of those studies that aim to compare continuous versus intermittent stimulation minimally comparable (e.g., compare some of the studies in table 2 of this review Part I)¹.

Continuity and Intermittency – Which is More Fatiguing?

Another more practical issue with comparing continuous versus intermittent stimulation is the conflicting literature, showing different opinions on the fatigue of muscles subjected to intermittent as opposed

to, continuous stimulation. While it has been suggested that intermittent (or “cyclical”) stimulation, with rest in between pulses is better in reducing fatigue than continuous stimulation by Krajl and colleagues,² this is not always the case. Differences in continuous and intermittent stimulation patterns have been investigated by various authors such as Spriet & colleagues.³ In their study of healthy quadriceps of 12 male subjects, Spriet et al.³ compared muscle responses between a continuous protocol of 102.4s stimulation, with an intermittent protocol of the same time, but delivered at a duty cycle of 1:1 (1.6s ON, 1.6s OFF). Stimulation was performed at 20Hz. The authors found in the first 51.2s, that isometric force decreased more for the intermittent group (to 55% of initial isometric force), compared with the continuous group (to 80% of initial isometric force). This would suggest that fatigue was greater after stimulation with breaks. Yet other studies such as that of Duchateau and Hainaut⁴ suggest relaxation will quell

Table 1. Postulate. Intermittent versus Continuous Stimulation

The fact that the relative ability of an intermittent protocol to be less fatiguing for a muscle compared to a continuous analogue, and vice versa for another muscle, warrants serious further investigation.

fatigue (Table 2, in review Part I)¹. Although their study was on adductor pollicis, stimulation was provided over a similar time frame of 60s under continuous stimulation. Therefore, the relative fatigue that intermittent and continuous stimulation may give is contested across the literature. This concept may be further concurred by examination of other studies. By the findings of Pournezam et al.⁵ and others (table 2, in part I)¹, it could be suggested that continuous electrical stimulation is much more fatiguing than intermittent, sequential stimulation. The authors do for example, argue that recovery is better for sequential as opposed to continuous stimulation. Their study also examined different types of sequential stimulation. They argued that 3-phase (i.e. RF, VL, VM) is better than 2-phase stimulation (RF, VL+VM), in the context of fatigue and recovery. However, other authors such as Duchateau and Hainaut⁴ argue that force decline is greater for intermittent, compared with continuous stimulation. There is no doubt that the methodologies employed by the authors were invariably different. In terms of muscles examined, one cannot directly compare quadriceps findings⁵ with that of adductor pollicis.⁴ Comparing these two papers provides evidence for the contention in the literature surrounding the relative effects of intermittent compared with continuous across different time domains. In light of these findings, an important postulate is put forward against the backdrop of the literature (Table 1).

Further Contentions?

The idea that a greater frequency of stimulation causes more fatigue may be contested by the findings of Matsunaga et al.⁶ The authors investigated duty cycles of 1/15, 1/30 and 1/60, by providing stimulation for 4s at the beginning of 60, 120 and 240s (i.e., 4s ON, 56s OFF; 4s ON, 116s OFF; 4s ON, 236s OFF as inferred from their data). Experiments were conducted in healthy individuals ($n = 20$), and suffering with paraplegia ($n = 4$). The paraplegic results are discussed here for illustrative purposes. Electrical stimulation was delivered as square monophasic waves, pulse width 200 μ s. In the paraplegic group, six different protocols were used, and fatigue was recorded. Protocols involved stimulation at 20 or 100 Hz with duty cycles of 1/15, 1/30, or 1/60. The authors used a strength decrement index (SDI) originally proposed by Clarke et al.⁷ to assess muscle fatigue, measuring quadriceps femoris torque with a KinCom isokinetic dynamometer. Interestingly, SDI was significantly greater after 20Hz stimulation than 100Hz ($n = 16$ tests). Moreover, SDI after 1/15 was significantly greater than after 1/60 (no

significant difference between 1/15 and 1/30, 1/30 and 1/60) but by manual inspection of their data there is a downward trend. Krajl et al.² put forward that fatigue can be reduced "...by using the lowest stimulation frequencies possible..." in their paper on ES standing for paraplegia. However, in a study Matsunaga et al.⁶ this would dictate otherwise. While context is important, such findings illustrate general differences in duty cycle and frequency relationships.

Is the Duty Cycle Reported?

The notion of continuous and intermittent stimulation differences is inextricably tied with the concept of choosing relevant ON and OFF times for exercise. This concept is important in all forms of FES exercise. However, in order to appreciate the true differences between continuous and intermittent stimulation, it is essential that the duty cycle is reported explicitly. The literature clearly indicates that duty cycle may not always be explicitly reported, or warrant in-depth analysis. Deley et al.⁸ for example, present a table of various studies and the duty cycles used by the authors. Papers listed include a collection of FES cycling, and muscle strengthening, papers. In all the FES cycling papers listed, they state that duty cycle is "not applicable". However, in most of the strengthening papers, duty cycles are presented. Indeed duty cycles are relevant, and are a cardinal feature of a train of impulses.⁸ Other than to facilitate the venture to have all FES protocols of a common nature, there are more important reasons as to why duty cycles should also be presented in all cycling papers as well.

Standardized Definition. Proposal 1. Domain Reporting

The relative ability of intermittent and continuous protocols to bestow fatigue upon muscles is thus conflicting, as illustrated from literature (Part I)¹ Therefore, it follows that some theoretical guidance could facilitate the development of a more unified approach to discussing the relative degree of intermittency as compared with continuity of electrical stimuli. A fundamental approach is outlined in (Table 2), with relevant literature discussed. It is believed this theory here will help to provide a more homogeneous basis upon which such disparities could be studied. In addition, examples of duty cycles in terms of "domains" (i.e., over what time unit the duty cycle or stimulation is expressed), is also presented in Table 2. It is pertinent to note in the discussion of domains, that stimulation in the seconds domain is of particular interest for muscle

Table 2. The Theory of Domain Reporting: A Fundamental Axiom for FES Protocols

Statement:

No electrical pulse train is purely continuous, as between pulses in the train there exists a series of interpulse intervals [e.g., Springer et al.^{9*}]. These intervals have to exist by the definition of frequency.

Definition:

An electrical pulse train is **truly continuous** if and only if the pulse width of the pulses in the pulse train multiplied by the frequency equates to a value of 1 [or any dimensionless multiple].

Implication:

For the sake of more commonality between FES protocols, there needs to be a standardized definition about what a “continuous” and what an “intermittent” pulse is. Moreover, the time domain of both interpulse intervals and pulses, as well as pulse train ON and OFF times should be reported in all FES protocols for the purposes of reporting total time ON and total time OFF of stimulation. In addition, such reporting is essential if comparisons between continuous and intermittent protocols are going to be drawn in the context of fatigue and other relevant metabolic parameters. This follows on also, from the postulate of table 4.

Relevant Literature – Examples of Continuous and Intermittent Comparisons:

- Chasiotis et al.¹⁰
- Duchateau & Hainaut⁴ – compared “sustained” and intermittent.
- Bergström & Hultman.¹¹

*Springer & colleagues discuss the “interphase interval”, however is referenced here as is an example of literature which talks of smaller breaks in stimulation.

contractions, whereas milliseconds stimulation is related to nerve fibre recruitment.

Pulse Width Reporting as Well?

One element tied to theory of domain reporting is pulse width, which helps determine how long stimulation is turned on for in the microseconds or milliseconds domains. Hence, accurate reporting of pulse widths between study is requisite, and a fundamental part of the theory presented here. Pulse width is usually specified by FES protocols that investigate duty cycle, for example Deley et al.⁸ facilitating a researcher who would try and compute the total charge from this, with the relevant ON/OFF time and current amplitude. However, a closer look at a publication by Bijak et al.¹⁹ could possibly make one draw skepticism to how pulse widths are reported. For example, in their work on FES standing and walking, the authors note that “...pulse duration 0.6 us + 0.6 us...” was used, in the context of biphasic pulses. In light of the Bijak et al.¹⁹ reporting, one must question whether these values refer to the total or partial pulse width calculation. In other words, are the authors reporting the duration for half the pulse, or the total pulse?

Issues with Duty Cycle Definition and Relevance

In designing training protocols, it is imperative to understand how changing parameters of stimulation influences various aspects of a muscle contraction. This was highlighted in a paper by Packman-Braun²⁰ in the

late 1980s in her study of wrist muscles in hemiparesis, when she put forward:

“Some compromise between quality and quantity may be required to create the optimum training protocol”²⁰

The authors also ask: is it better to do more contractions, or less but

“... at a higher ... force output”²⁰

Such a question highlights the importance of considering the training protocol in the design of a study, in addition to the parameter protocol implemented. Furthermore, Packman-Braun²⁰ argue that if OFF time increases, there will be less muscle contractions, and that there is an inherent act of balancing when considering treatment.

Critical Analysis – Definition and Varied Reporting

A commonality that exists amongst the literature of ES is of course contention in both the best stimulation sequences to use, and definitional aspects of FES. This is why it is important to have a rigorous understanding of the definition of an electrical parameter. Duty cycle is often reported in different ways between authors, as highlighted in Table 4. Whether explicitly reported, or inferred, duty cycle differs between studies not just in terms of stimulation time ON compared with stimulation time OFF, but in what time domain this occurs. Indeed, the idea of time “domains” is the basis of the author’s derivation of a system for reporting duty

Table 3. Domains of Different Duty Cycles

Milliseconds domain:

- **Laughman et al.¹²:** “10msec of sinusoidal output, 10-msec silent period”* Quadriceps, healthy humans.

Seconds domain:

- **Dreibati et al.¹³:** 60 X 5s ON, 15s OFF for 20mins. Performed at 100, 50 & 20 Hz. Quadriceps, healthy humans.
- **Gondin et al.¹⁴:** [A variety of papers presented by authors stipulating different duty cycles across studies].
- **Gorgey et al.¹⁵:** 3s ON, 3s OFF, for 1min.
- **Chou and Binder-Macleod¹⁶:** 1s ON, 9s OFF [inferred from their SCI protocol], their “testing trains”].
- **Matsunaga et al.⁶:** 1/15 (4s at start of 60s), 1/30 (4s at start of 120s), 1/60 (4s at start of 240s).
- **Giannasi et al.¹⁷:** 12-19mA 5s ON 10s OFF 20mins. Stimulation of masseter and temporalis.

*Minutes domain**:*

- **Minogue et al.¹⁸:** 4 min stimulation, 4 min rest. However, the authors suggest that the 4 min were comprised of 5s ON 5s OFF periods.

* *May be referring to an alternating current (AC) equivalent of an IPI.*

***Not actually minutes domain, but seconds domain. However, placed here for discussion.*

cycle in a common fashion between studies. To illustrate by example, the study by Minogue et al.¹⁸ reported stimulation as lasting 4 minutes both ON and OFF. However, studies by authors such as Dreibati et al.¹³ all utilize duty cycles which involve stimulation ON and OFF time in the domain of seconds. Therefore, the theorem presented in Table 3 could facilitate better understanding of what duty cycle is used by researchers if they adopt this paradigm. An example of a study where the reporting of duty cycle can be met with confusion is that of Song et al.²¹ The authors developed software to be used with an 8 channel stimulation system. They specified that duty cycle could be changed in the range 0-10s. There are questions which may come to mind when analyzing this statement. What exactly is being reported? Is this referring to ON or OFF times, or both ON and OFF times? Are ramp-ups/ramp-downs included? Also, a diagram of the software is presented by the authors which has a depiction of ramp up/ramp down, but it is unclear from the authors’ work whether or not this is included in the “duty cycle”. Such observations are just one example of contentions which stem from duty cycle literature. An account of literature inconsistencies is listed in Table 4, with important concepts related to duty cycle reporting variability. An issue which stems from the literature is that of notation, with different authors reporting duty cycles by use of different methods (Table 4). For example, in the review by Deley and colleagues,⁸ the authors present duty cycles from various researchers in terms of “dashes”, such as 5-5 when reporting the work of Bélanger et al.²² Yet duty cycle is presented as fractions by Matsunaga et al.⁶ and percentages by Lieber and Kelly.²³ Inter-conversions between such notations may be rendered confusing, preventing transparent comparison across

studies. For example, Gondin et al.¹⁴ also reported duty cycles [of Herrero et al.^{24,25}] as 2/1. Herein these are discussed, using the Gondin et al.¹⁴ interpretation of the literature consulted. Confusion may arise when comparing this with for example, Matsunaga et al.⁶ duty cycles. These authors stipulate a duty cycle of for example, 4s every 60s (so 1/15, or 6.667%). If one was to convert Herrero et al.^{24, 25} 2/1 to a percentage this would imply that stimulation is on for 200% of the time. In parallel, in their study of denervated muscle, Ashley et al.²⁶ used duty cycles of 1/2 or 2/1 depending on what stimulation pattern they were investigating. By their notation, these would be 1s ON 2s OFF or 2s ON 1s OFF. Hence, this “fractional notation” may not be all that convoluted. Yet, if comparing with a protocol which utilizes percentage notation, care must be taken not to misinterpret a 2/1 duty cycle as a “200% duty cycle” which has not realistic meaning. In this situation, what this definition means is that the duty cycle is defined relative to the OFF time. The ON time is 200%, OFF time is 100%, yet this sounds arduous. Finally, caution must be taken when comparing studies on a basis of their duty cycle findings, if one uses alternating current, the other pulsed current. An example of some confusion that may arise from the literature may be seen in examining the work of Moreno-Aranda and Seireg.³³ Although the authors work was performed using AC stimulation of canine quadriceps, it does elucidate some important considerations when duty cycles are reported in alternating current studies. For example, the authors concluded that “maximum pull” for the dogs occurred at an “ON-OFF frequency” of 50 Hz, and at a duty cycle of 50%. This would suggest that “ON-OFF” and “duty cycle” are not synonymous. However, the authors do stipulate that the term “duty cycle” refers to: “*Ratio of*

Table 4. Examples of Duty Cycle in The Literature and Contentions

Issue	Example from Literature
#1: Different notation used to denote duty cycle	<p>Fractional notation. Matsunaga et al.⁶ report “periods” of stimulation as a fraction of a certain period. E.g. 4s at beginning of 60s period = 1/15.</p> <p>Descriptive notation. Minogue et al.¹⁸ report “...bouts of intermittent NMES, each bout lasting 4 minutes, with a rest interval of 4 minutes between each bout”. [Yet stimulation is delivered in the seconds domain within these minutes, also].</p> <p>Descriptive notation. Currier and Mann^{27*} report a long-winded description of a 15s ON (5s ramp, 10s peak intensity), 50s OFF protocol</p> <p>ON/OFF notation. Carmick²⁸ report “...10 seconds on and 25 seconds off...”, for example.</p> <p>Percentage notation. Lieber and Kelly^{24***} report “ 50% duty cycle (5 s stimulation, 5 s rest)*** ”</p> <p>Dash notation. Deley et al.⁸ presents duty cycles from a variety of literature. One such example is “5-5” from Bélanger and colleagues,²² who report in their study “...5-sec on/5-sec OFF duty cycle...”. Another example is their reporting of Cramer et al.’s²⁹ duty cycle as “4”.</p>
#2: Duty cycles are often reported but the domains**** are different across studies.	See Table 3.
#3: Duty cycles sometimes***** include ramp up and ramp down times, sometimes do not.	e.g., Baker et al. ³⁰ stipulates that ramps not usually included in duty cycle time. But shouldn’t they be as they indicate when stimulation is on?
#4: Sometimes information may be missing from the reported duty cycle (explicitly or implicitly reported DC’s), hence it is hard to know what the exact duty cycle is.	e.g., Soo et al. ³¹ showed that quadriceps torque increased after a protocol of 15s ON (5s ramp, 10s ON), but they did not report OFF times between contractions.

*[Regarding: Currier and Mann²⁷]: “Tetanic isometric muscular contractions lasted for 15 seconds, during which time the current was surged so that peak intensity was reached after 5 seconds and sustained for 10 seconds. At the end of the 15-second current stimulating period, the intensity abruptly declined and was followed by a 50-second rest before the next stimulating period (isometric producing repetition).” (Currier and Mann, 1983).

**[Regarding: Lieber and Kelly²³]: The authors report: 50% = 5s ON 5s OFF, 70% = 5s ON 2s OFF. Yet $5/7 * 100 = 71.43\%$ ON...so they may be roughly accurate. A good idea would be for the authors to rather rename their study one which focuses on the effects of different relaxation time intervals, to be more precise.

***This is also a modified ON/OFF notation as well. E.g. “...stimulation....rest...”²³.

****The author of this paper proposes notation for duty cycle domains.

*****Janssen and Pringle³² mention 5s rest...how long are contractions?

time ON and OFF of the stimulation signal”.³³ While all the literature has aimed at advancing our understanding of different stimulation regimes for FES, it is clear that a more common method for reporting duty cycle is desirable.

Standardized Definition. Proposal 2: Duty Cycle and Duty Cycle Multiplicity

Duty Cycle Definition

Let the **duty cycle** be defined in the following unambiguous manner:

$$\text{Duty cycle} = X \text{ s ON, } Y \text{ s OFF}$$

$$\text{With a RU of } Z \text{ s and RD of } W \text{ s}$$

Where:

- X s ON denotes stimulation which is on (ON) for X s,
- Y s OFF denotes stimulation which is off (OFF) for Y s,
- RU of Z s denotes a ramp-up (RU) time of Z s,
- RD of W s denotes a ramp-down (RD) time of W s.

This notation of ON and OFF is used extensively to describe, and is derived from, the literature presented in part I of this review.¹ The form above is one with minimal ambiguity, allowing for full information of the duty cycle to be described. In a practical sense, this is illustrated with some examples:

- *The duty cycle is 2s ON 3s OFF (RU = RD = 1s).*
- *The duty cycle is 1s ON 5s OFF (RU = 2s, RD = 0.5s).*

In the second example, there is a greater ramp-up. In the first, ramp-up and ramp-down are the same.

Duty Cycle Multiple – T_f

What is more important is the concept of ambiguity, as discussed previously. For example, a 2:10 and 1:5 both are a 1:5 duty cycle, but with different **multiples** of 2, and 1, respectively (i.e., 1:5 = 1:5 X 1, 2:10 = 1.5 X 2). Let this be the **duty cycle multiple (T_f)**. It follows from the above example, that the duty cycles may alternatively be expressed in a format with a **fundamental duty cycle** (FDC) and corresponding T_f as such:

1:5 ($T_f = 2$), 1:5 ($T_f = 1$) respectively.

Wherein the term “fundamental” could be thought of being inspired by engineering and physics concepts related to “fundamental frequency”. While of course this, with this definition, it may be seem to be “playing with semantics”, indeed specification of the duty cycle multiple is useful in the design of experiments when comparisons of several duty cycles are being made, to see which ones have the same percentage ON and OFF time (an FDC with any multiple having the same percentage of time spent ON and OFF). For example, Baksay,³⁴ in his thesis examining ON and OFF times for thigh stimulation, used duty cycles of 5:15, 10:30 and 15:45. By the notation presented, these would correspond to an FDC of 5:15, and T_f values of 1, 2 and 3, respectively. This reference is just one example of literature where the **same** duty cycle is used, with different multiples (e.g., Gentz and Moore³⁵ from Part I¹). There are also other studies where only one of ON or OFF is permuted (see Smit and colleagues below, for example).⁴⁸ Therefore, the use of the T_f notation can be modified accordingly. For example, in another work we have used the duty cycles of 1:3, 2:3 and 3:3.³⁶ This could be represented as:

1:3 ($T_{f, ON} = 1, 2, 3$),

to denote the set of duty cycles tested. In that work, we also tested duty cycles where OFF time was doubled and trebled and both ON and OFF also. Therefore, to comprehensively represent the set of seven duty cycles tested, a set notation could be adopted:

1:3 ($T_f, T_{f, ON}; T_{f, OFF}$) = (1, 2, 3; 1, 2, 3; 1, 2, 3).

In this case we have a special example of when permutations are all the same so this could be further contracted as such:

1:3 ($T_f = T_{f, ON} = T_{f, OFF} = 1, 2, 3$).

Stimulation Ramp Times

While ON and OFF times are important in specifying a duty cycle, so too are ramps. Ramp times are times taken to turn stimulation up to a desired value, or to turn

down from that value to baseline (in this discussion, the focus is current amplitude). However, increase of pulse width has also been described, for example in Benton and Montgomery.³⁷ Respectively, these are known as the “ramp-up” and “ramp-down” times. Hence, as they are related to ON and OFF times, they warrant mention in any “duty cycle” discussion. Moreover, they have an important influence on the contractile manifestation of muscle movement that occurs due to an applied stimulus. It has been discussed in literature on FES-walking by Bijak and colleagues, that ramp times are essential for providing “...*natural movement*...” as opposed to sudden ON/OFF stimulation,¹⁹ that would lead to considerable sporadicity in movements. Ramps are often reported in cycling studies, such as Sijbert et al.³⁸ Another matter of contention to stem from the literature relates to the inclusion, or exclusion, or ramp-up times in the duty cycle numbers. Baker et al.³⁰ stipulate that usually ramp up and ramp down are not included in the duty cycle definition. Yet, in the same publication, the authors discuss how there is an inherent variability with different stimulators, in the context of how ramp up and ramp down are included in ON and OFF definitions. The authors stipulate that OFF time should be determined by the “plateau ON time”.³⁰ In an early paper by Baker et al.³⁹ the authors stipulate that “...*the stimulation cycle lasts for seven seconds, followed by a 10-second rest interval*”. They then say that in the ON time, stimulation increases over 3s to the max (exponentially), then is held there for 4s. Therefore, ramp times may be reported in various ways across studies. Not only does the inclusion of ramps in ON/OFF times vary across FES equipment, but also between various research groups. Packman-Braun for example,²⁰ defined 7s ON time as being comprised of; 2-s ramp-up, 5-s contraction in their study of wrist extensors. Duty cycles were defined relative to 5s ON time.²⁰ This variation in definitions of ON and OFF that exist between stimulators and authors render cross-study comparison difficult. This also suggests that a superficial reading of papers which examine duty cycle can lead the reader to make false conclusions, unless they truly understand how “duty cycle” is defined, and whether or not ramp-up and ramp-down times are included in its’ definition. The precise reporting of ramp-up times is also an important consideration when discussing duty cycles, as such timing may change over time according to the treatment purpose. Carmick, for example,⁴⁰ comments on how ON times can be reduced over time, for children with cerebral palsy after they have become comfortable with the electrical stimulation used. Carmick also changed ramp-up times from 8s to 2s in her study of ES for cerebral palsy.²⁸ Similarly, Carmick also changed ramp-up from 8s to 2s,⁴¹ in accordance with comfort, in her study on upper limb ES in cerebral palsy. Carmick focussed on lower limb.²⁸ In the 1993a study,²⁸ the author also noted that when ES was required to control gait, 0.5s ramp-up was utilized.

Table 5. Duty Cycles and Pressure Sore Attenuation

- **Baker et al.**^{45*} conducted a study on individuals with spinal cord injury to examine the effects of three different stimulation patterns on wound healing of pressure sores. They argued asymmetrical biphasic is the best type to use. In all cases, a 7:7 was utilized. This illustrates a 1:1 duty cycle can be used to attenuate pressure ulcers.
- **Bogie et al.**⁴⁶ also investigated use of ES for pressure sores. The authors report a case study of one participant (C4 SCI) with implantable percutaneous electrodes. The stimulation was of the glutei, 20Hz, 8s ON 4s OFF (initially), followed by 20Hz 15s ON 15s OFF (second phase – a “dynamic” protocol in concordance with what the authors stipulate is important to prevent tissue wastage. The authors discovered that upon using ES, tissue oxygenation of the ischial region decreased.
- In a larger trial, **Van Londen et al.**^{47**} also investigated use of surface ES for pressure sores, in 13 individuals with SCI. They compared stimulation delivered to each glutei at once (“simultaneously”) with that delivered to each gluteal in succession (“alternately”). The simultaneous protocol was 0.5s ON 15s OFF for both glutei at the same time, whereas the alternating protocol was given as 0.5s ON 15s OFF with one glutei by itself followed by the other. The authors concluded that the various pressures measured did not differ between alternating and simultaneous protocols.
- **Smit et al.**⁴⁸ compared duty cycles of 1:1, 1:4 (1s domain) for 3h of stimulation of hamstrings and gluteals in SCI. 1:4 was found to have a greater decrease in ischial tuberosity pressure, and less fatigue than 1:1.

Salient Remarks:

- *[Regarding: Baker et al., 1996]: Asymmetrical pulses were 100us, 50Hz, 7:7. Symmetrical pulses were 300us, 50Hz, 7:7. Care must be taken in interpretation of the results, as the pulse width of the asymmetrical pulse was one-third that of the symmetrical pulse. Also tested were microcurrent pulses – 10us, 1Hz, 7:7. By the proposed notation of this paper, this is a 1:1 duty cycle, with $T_f = 7$.
- ** The authors state in their crossover study design that 15mins rest was given between stimulation using another protocol. Yet, other authors usually give 48hrs (e.g., Baksay³⁴) in between stimulation sessions for example. One could argue that the works of Van Londen et al. (2008) may have disregarded this fatigue.
- ***[Regarding: Van Londen et al., 2008]: One could argue that there would have possibly been some differences should this protocol be repeated with some further rigour. For example, the alternating protocol involved 0.5s ON 15s OFF on one glutei, then 0.5s ON 15s OFF for the other for 60 total repetitions (31mins total, with 15.5mins each glutei). The simultaneous protocol involved 0.5s ON 15s OFF on both glutei for 120 total repetitions (31mins total, with 31mins each glutei). It is clear from these simple calculations that the simultaneous protocol involved stimulation for each glutei twice the time of the alternating protocol. The simultaneous protocol could have been done for 15.5mins total to ensure comparable stimulation times between the two protocols.

In addition, stimulation was given initially at 10s ON 25s OFF (i.e. 1:2.5), then changed to 15s ON 15s OFF (i.e. 1:1) when the patient gained comfort with the protocol. Long ramp-up times of 12s have also been reported, in stimulation contexts where current as high as 300mA has been used such as was the case in a study by Janssen and Pringle.³² Ramp-down times have also been included as a variable in the ON timing for stimulation. On the basis of prior art [namely, Jubeau et al.⁴² and Lyons et al.⁴³], Aldayel et al.⁴⁴ defined the ramp-up and ramp-down characteristics of their stimulation protocol for studying the differential effects of alternating EMS and pulsed EMS. The authors note that they used a 25% duty cycle (5s ON, 15s OFF). The

5s ON was inclusive of a 1s ramp-up, and a 1-s ramp-down. Hence, the total time at maximum stimulation in each 5s session was 3s. It is thus apparent that the true meaning of “ON” time is somewhat obfuscated in light of the various differences in study designs which choose to either include or exclude ramp-up/down times from the ON time definition. It is important that precision is taken into serious consideration, in light of studies such as Bijak et al.¹⁹ which argue that ramp-up times in FES walking for example, are dependent on the mass of the patient. The authors argue that ramp time is a pertinent issue in the context of optimization of FES standing. They stipulate that fast ramps (i.e., 0.2s) are more suitable for patients with a heavy weight, while longer

ramps (i.e., 0.4s) are better in patients with a smaller weight.¹⁹

Case Studies in Light of the Proposed Frameworks

The duty cycle is an important parameter to modulate when controlling FES-evoked exercises. Here we illustrate the use of the novel proposed conceptual ideas, when describing some of the literature regarding two distinct examples: stimulation for pressure sores, and FES-cycling.

Case Study 1: Pressure Sores

While the duty cycle has been examined in the context of fatigue and differential metabolic effects (Table 2, in review Part I)¹, it has also been studied in the context of pressure sores. Relevant results are here discussed in Table 5. As previously reported,¹ these studies are summarised in chronological order. Examining the stimulation parameters of Smit et al.⁴⁸ more closely, the authors used duty cycles of 1:1 and 1:4. As these were in time multiples of 1s, by the T_f notation, this can be represented as having performed stimulation at 1:1 ($T_{f, OFF} = 1,4$). This allows focus to be drawn on the ON or OFF (in this case, OFF) time that is being permuted. As seen in Table 2 of Part I,¹ the domain of stimulation has also been annotated.

Case Study 2: Duty Cycles and FES Cycling

There are many types of FES exercise available, such as FES-cycling, FES-rowing and FES-exoskeletons.³⁶ However, FES-cycling is widely reported across the literature. Therefore, insights into duty cycle reporting may be derived from FES cycling research. In the context of ES cycling, stimulation is usually reported for muscle groups in terms of the angles of the cadence through which certain groups are turned on (e.g., Berkemans).⁴⁹ By this observation, it seems that duty cycle need not be reported – angles of the cadence clearly can be used to calculate how long a muscle is switched on per revolution. However, in light of recent work by Fornusek et al.,⁵⁰ it would be helpful to the field of FES if these ON and OFF values could be converted to percentages or fractions (such as, e.g., Matsunaga et al.⁶), to allow for comparison of the outcomes of cycling studies with isometric studies. For example, Fornusek et al.⁵⁰ compared isometric and concentric exercise. Furthermore, if there were a common way of reporting duty cycles then perhaps these results could be compared more easily with other studies, and comparisons between cycling (rpm indicative of duty cycle) and isometric (s ON s OFF indicative of duty cycle) could be made.

Conclusive Summary

The duty cycle is an important electrical stimulation parameter insofar that the degree of continuity or intermittency as defined by it can have differential effects on muscle characteristics, including fatigue. In Part I of this review,¹ we showed that its' definition

differs across literature, and we presented a survey of the pulsed current literature with critical commentary. This work can hopefully be used by researchers who are conducting studies examining how duty cycle affects fatigue, through providing an overview of how others have attempted to understand this parameter. In addition to the review presented, meta-analyses could be further conducted in the future which look at duty cycle. A meta-analysis could *stratify* electrical stimulation studies on a basis of: a) acute vs chronic studies (i.e. does the study look at bouts of 10 contractions etc., or does it look at an intervention over time for a few weeks?), and/or; b) duty-cycle-focused vs non-duty-cycle-focused (i.e. does the study aim to look at the effects of different duty cycles, or is this a secondary outcome of the study?). The papers presented highlight issues which need to be addressed in terms of duty cycle reporting, which could provide the basis for such a review. In 1988, Packman-Braun²⁰ argued that there needs to be “clarification” of using duty cycles with desirable fatigue responses, in order to allow, among other things, that “...the various therapeutic effects of treatment with FES will not be undermined by a poor choice of stimulation characteristics”.²⁰ While authors such as Baker have done tremendous work in presenting therapeutic indications with duty cycle in consideration,³⁰ this review has shown there is still more fundamental work required in terms of precision in study reporting.¹ In part II, we proposed the concepts of domain reporting, and duty cycle notation.⁵¹ This was done in the backdrop of literature that variably reports on duty cycle. Therefore, we hope these concepts will broaden the FES community's understanding of duty cycle reporting while also becoming aware of its' significance. Perhaps one step in the right direction in highlighting the importance of this parameter was a recent patent by Ranu (USPTO 9,643,010 B2) which details a system focused on the duty cycle.⁵² While frequency, pulse width and amplitude are more well-described across the literature, it is evident that focus on duty cycle is required for a complete picture of the stimulation specification when muscle is subjected to FES. These two reviews have provided a substantial overview of the literature pertaining to the duty cycle in Functional Electrical Stimulation applications. However, future work would also be well-guided to examine the influence of duty cycle modulation in situations where stimulation is delivered for multiple hours during the day. This has been explored for example in the work of researchers examining latissimus dorsi stimulation following cardiomyoplasty,⁵²⁻⁵⁷ where it has been suggested to provide periods of rest as opposed to continuous daily stimulation. In addition, use of FES in healthy and weakened/pathological muscles requires different training protocols. Therefore, consideration of the duty cycle across various muscle conditions would also be of immense interest in clinical FES uses, in particular for

managements of transiently and permanent denervated muscles.⁵⁸⁻⁸⁴ New rehabilitation strategies developed in Vienna and the commercial availability of a purpose developed electrical stimulator (Stimulette den2x)⁸⁵ and large electrodes open new hopes to spread world-wide managements to recover long-term permanent denervated human muscles by Home-based FES.⁶¹⁻⁷² Furthermore, we are confident that our suggestions will be followed in the training of those thoracic-level SCI persons after their enrollment in the future studies on FES intrathecal approaches.⁸⁷⁻⁹⁸ Taken together, these applications show the clinical importance of understanding differences in continuous and intermittent stimulation. Therefore, further exploration of duty cycle modulation in FES exercise across different patient cohorts is justified and mandatory.

List of acronyms

AC – alternating current
ES – electrical stimulation
EMS – electrical muscle stimulation
FDC – Fundamental Duty Cycle
FES – Functional Electrical Stimulation
Hz – Hertz
IPI – interpulse interval
RF – rectus femoris
SDI – strength decrement index
 T_f – Duty Cycle Multiple
VL – vastus lateralis
VM – vastus medialis

Author's contributions

MJT drafted the manuscript and was responsible for literature review and critical synthesis and analysis of literature, CF and AJR gave feedback on the manuscript.

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Conflict of Interest

The authors declare no conflicts of interests.

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