Reducing Muscle Fatigue in FES Applications by Stimulating with N-Let Pulse Trains

Zopher Z. Karu, Student Member, IEEE, William K. Durfee, Member, IEEE, and Aaron M. Barzilai

Abstract—Applications of electrical stimulation for restoration of functional movements such as standing, gait, and grasp have always been hindered by the rapid fatigue of stimulated muscle. This paper describes an experimental investigation of stimulation with N-lets (a set of N closely spaced stimulation pulses) as a means of producing contractions with improved fatigue characteristics. Experiments were conducted on 27 able-bodied and four SCI human subjects using surface stimulation of the quadriceps muscle to produce isometric knee joint torque. Based upon evidence from the literature on muscle fatigue, parameters of the N-let trains for N = 1–6 were optimized to produce the most force per pulse. The results demonstrated that: 1) nonlinear summation of the twitch response occurs in human subjects with N-let surface stimulation; 2) for most subjects, doublet stimulation (N = 2) with a pulse interval of about 5 ms produced the maximum torque-time integral per pulse of the resulting twitch; and 3) on average, optimal N-let stimulation resulted in a 36% increase in isometric torque tracking when compared to traditional singlet stimulation. The results have immediate implications for alleviating the problem of premature fatigue during functional electrical stimulation.

I. INTRODUCTION

A. Background

FUNCTIONAL electrical stimulation (FES) has shown promise as a rehabilitation technology for a number of disabilities caused by weak or absent muscular function. FES enables individuals with lower limb paralysis from SCI or stroke to stand and, in some cases, achieve limited gait [15], [29], [30], [34]. FES has also been used to restore partial grasp, elbow, and shoulder function to SCI quadriplegics [6], [42], [44], [46]. Other uses of skeletal muscle FES include augmenting ankle dorsiflexion for cases of foot drop [36], [61], sacral nerve stimulation to correct urinary incontinence [8], and cardiomyoplasty where a skeletal muscle such as the latisimus dorsi is surgically wrapped around the heart and stimulated to improve compromised cardiac function [12].

All of these applications require that the stimulation provide strong, consistent muscle force. It is well known, however, that muscle fatigues far more rapidly when artificially stimulated than when excited by the central nervous system. As a result, successful implementation of FES paradigms for rehabilitation have been greatly limited by premature fatigue. The reasons for rapid FES fatigue are not entirely understood but are believed to include the shift toward fast-fatiguing muscle fibers that occurs in denervated muscle [27], the inverse size-order recruitment of axons resulting from activation with external electrodes [26], [40], [53], and the unnaturally high rate of motor unit activation and accompanying rapid transition to ischemic conditions that results from the synchronous activation of axons with FES [3], [5], [57].

Many techniques have been developed to help alleviate the problem of FES-induced fatigue. Before participating in clinical studies of FES-aided standing, gait, or grasp, subjects routinely undergo a regular exercise protocol of electrical stimulation over several months which strengthens the muscle and reduces fatigue through a gradual shift in muscle fiber metabolism from fast-fatiguing to fatigue-resistant fibers [28], [37], [43], [47], [48], [55], [60]. Normal size-order recruitment can be achieved though nerve cuff electrodes and special stimulation techniques such as high-frequency block [2], [63] or trapezoidal waveform excitation [22], [23]. Multiple surface, intramuscular, nerve cuff, or intrafascicular electrodes can be used to implement a coarse form of sequential stimulation among sets of muscle motor units to lower the stimulation frequency seen by any one muscle fiber, and hence more closely imitate the asynchronous behavior of the central nervous system [49]–[52]. Despite these efforts, fatigue continues to be a limiting factor in the wide-spread application of FES techniques in rehabilitation practice.

This paper presents an alternative method for combating FES fatigue. We have found that using optimized N-let (a set of N closely spaced pulses) stimulation trains greatly increases the ability of a stimulated muscle to sustain force during an isometric contraction when compared to stimulation using the single pulse trains of conventional FES. The N-let stimulation method is simple to implement and can be applied immediately to existing FES systems. It also can be readily combined with other fatigue-reducing measures. This paper discusses the rationale for investigating N-lets, then describes a series of experiments in able-bodied and SCI subjects to test the hypothesis that optimized N-let stimulation reduces fatigue. Fig. 1 introduces the N-let terminology and parameters used throughout the paper. Preliminary results of this work were presented in [33] and complete details can be found in [32] and [4].

0018–9294/95$04.00 © 1995 IEEE
B. Rationale for Using N-Lets

It is well known that during sustained isometric stimulation, muscle fatigue is a strong function of stimulation frequency with higher frequencies resulting in a faster rate of force decline [7], [13], [35]. There is also evidence which demonstrates that fatigue can be directly related to the total number of stimulation pulses received, independent of stimulation frequency [25], [39]. Our preliminary experiments (described in Section III) also support this theory. Based upon this evidence, the premise for our work was that to minimize fatigue, practical FES systems should aim to produce the most force per stimulation pulse.

Mammalian motor units are known to exhibit a nonlinear summation of twitch force when activated by doublet stimulation (a pair of closely spaced stimulus pulses). That is, the twitch force amplitude resulting from doublet excitation is more than twice the amplitude of twitches produced by singlet stimulation. This phenomenon has been demonstrated in animal model work using single motor units [10], [11], [59], [62] and isolated whole muscle [14], [45], as well as in single motor units of intact human muscle [21]. Doublet discharges have also been found to occur naturally during normal human movement, particularly at the start of ballistic motions [16], [17], [56] and during tremor [21], [38]. Therefore, we wished to explore the possibility that exploiting this nonlinear property would lead to more “efficient” stimulation methods.

Although the physiological basis of nonlinear summation is not known, Parmigiani and Stein have speculated that an increase in internal stiffness or calcium release mechanisms may play a role [45]. It has been shown, however, that the nonlinear summation in force by a doublet is due to an intrinsic property of the muscle fiber itself rather than the result of recruitment of additional motor units by the second pulse. For example, definitive evidence was provided by Elek et al. who used microstimulation to elicit nonlinear summation doublet twitches of single motor units in human first dorsal interosseous muscle [21]. Burke et al. concur that the phenomenon takes place in the muscle fiber [10], [11]. Our own work with EMG measurements during doublet stimulation (as described in the Section III) is consistent with this theory.

C. Objectives

Our study had three objectives: 1) to determine whether the nonlinear summation due to closely spaced stimulation pulses applies for surface stimulation of human skeletal muscle; 2) to expand the study of nonlinear summation to more than two pulses and to identify the optimal N-let pulse train parameters which would produce the most force per pulse; and 3) to verify our hypothesis that optimal N-let trains would allow for significantly longer muscle contractions during FES.

II. METHODS

A. Equipment

All experiments involved isometric stimulation of the quadriceps muscle of human subjects using surface electrodes. One channel of a computer-controlled custom stimulator was used for generating stimulation pulse trains. The stimulator’s transformer coupled output stage produced current-controlled, asymmetric, biphasic pulses whose amplitude and width were set by the computer. Each pulse was issued through a computer-generated triggering signal, thus providing the ability to generate arbitrary stimulus patterns with a resolution of 1 ms. A pair of self-stick, conductive carbon electrodes (Empi model 6300) were fixed to the skin over the quadriceps muscle according to the guidelines listed in [1]. Subjects were seated on a custom experiment bench and knee joint torque was measured with a strain gage force transducer fixed to a lightweight brace which was attached to the shank. In some preliminary experiments, a bipolar surface EMG electrode was positioned between the distal stimulation electrode and the patella with the ground reference placed on the shank. All experiments were under the control of a 33-MHz 386 PC. Torque data was sampled at 1000 Hz when measuring twitch response and at either 200 Hz or 40 Hz when measuring the response to continuous stimulation. EMG signals were sampled at 1000 Hz. Full details of the equipment and protocols can be found in [32] and [4].

B. Subjects

Tests were conducted on 27 male and female able-bodied subjects ranging in age from 19 to 38, and on four paraplegic subjects, one female and three male. The spinal cord injured subjects were drawn from a parallel study of FES-aided standing and gait [18]-[20]. As part of that study, subjects stimulated their quadriceps muscles for one hour each day and exercised on a FES-aided bicycle three times a week. Thus, there were presumably some training effects which converted a portion of their muscle fibers from fast-fatiguing to fatigue-resistant. The ages of the SCI subjects were 28, 46, 34, and 34 years; the injury levels were T6, C5/6, T10, and T5; the times since injury were 2, 25, 4, and 12 years; and the times participating in our FES gait program were 12, 24, 6, and 6 months. Not all of the subjects participated in all phases of the experiments.
C. Protocols

Subjects were seated on the bench with the knee joint locked at approximately 90° of flexion. Able-bodied subjects were instructed to relax to avoid contamination of the results by voluntary contractions. Experienced subjects were generally able to do this without difficulty.

The stimulation pulse width was fixed at 300 μs while the amplitude was adjusted individually. For able-bodied subjects, the maximal tolerable pulse amplitude during a continuous 40-Hz singlet train stimulation was determined in order to set a ceiling for subsequent tests. For SCI subjects, the maximum amplitude was set based on protocols used by our research group for standing and gait studies.

The first part of the experimental protocol was designed to identify the “optimal” N-let parameters, which included the number of pulses in the N-let (N), the pulse intervals (PI’s) within the N-let and the N-let period (NP). Fig. 1 illustrates how these parameters were defined. Our criteria for choosing the optimal N and set of PI’s was based on maximizing the per pulse torque-time integral (TTI) of the twitch, a performance index that has also been used by others [11], [31].

A sequential optimization search was implemented to determine the best set of PI’s for each N-let. Starting with N = 2, a train of 20 N-lets was issued with a spacing of 1 s between each N-let and with PA set at the maximum. The PI’s for the N-lets within the train were randomly varied between 2 and 20 ms in 2-ms increments with each PI being issued twice. The optimal PI was found by identifying the interval that resulted in the maximum average TTI. For N = 3–6, the procedure was repeated, but only the final interval in the N-let was varied with all prior PI’s being held constant at their previously determined optimal values. The entire procedure for N = 2–6 was repeated three times for each subject with the results averaged. The validity of the sequential optimization method was confirmed in a preliminary test which compared sequential and global optimization techniques for finding the best PI’s in triplet pulse trains [32].

The optimal value of N (number of pulses in the N-let) was also determined by measuring twitch responses. In this phase of testing, only PI-optimized N-lets were used with N ranging from 1 to 4. (In preliminary experiments, we tested N from 1 to 6.) A train of 60 N-lets was issued consisting of 15 repetitions of the four N’s in random order. The N-let which produced the highest average TTI per pulse was selected for the optimal value of N.

N-let period (NP) was determined by testing subjects with a series of 5-s long singlet and optimized doublet and triplet stimulation trains. Each set contained pulse trains at one of four fixed NP’s. For singlets, NP’s tested were 25, 40, 55, and 70 ms; for doublets, 50, 80, 110, and 140 ms; and for triplets, 48, 75, 111, and 150 ms. (Optimal NP’s were not determined for N in the range four to six because all subjects indicated either two or three for the optimal value of N.) Pulse amplitude was set to produce about 10 Nm of torque when stimulating with singlets at 40 Hz. For each 5-s torque record, the average torque from the middle three seconds was computed and divided by the total number of pulses issued to arrive at average torque per pulse. The N-let spacing that produced the highest average torque per pulse with no more than 13% torque ripple was chosen as the optimal value of NP. The latter requirement was important because setting NP too high produced widely spaced pulse bursts that resulted in high average torque per pulse but with unacceptable ripple.

To evaluate whether optimized N-let trains reduced fatigue, the performance of singlet stimulation was compared to optimized N-let stimulation in an isometric torque tracking task. A feedback control program varied stimulus amplitude, increasing the current as the muscle fatigued to maintain a specified torque level (generally in the range of 10 to 15 Nm) for as long as possible. Tracking time was calculated from when the measured torque initially came within 1 Nm of the target torque until the time when stimulus amplitude had reached its maximum value and the recorded torque had dropped below 75% of the target. The subject was tested first with singlets and then with optimized N-lets with a rest period of 15 min between trials. To prevent order from biasing the results, the test was repeated on a second day with the order reversed. This paradigm of testing fatigue through torque tracking was chosen to simulate what might occur in a FES application such as standing, where a closed-loop controller would adjust the stimulus to counteract fatigue.

III. RESULTS

The results are presented in three sections. First, typical fatigue trials and the nonlinear summation of force resulting from doublet stimulation are demonstrated. Second, results from N-let optimization and isometric torque tracking using N-let trains for able-bodied subjects are presented. Third, similar results for a small number of SCI subjects are presented. All results are from isometric stimulation of the quadriceps muscle.

A. Doublet Properties

Fig. 2 presents typical results for muscle fatigue during isometric stimulation. The top plot shows the drop in torque versus time for three singlet stimulation frequencies, while the bottom shows the same data plotted as a function of the total number of pulses received. It is apparent that fatigue, or the decline in muscle force output, was strongly correlated to the number of pulses received, supporting the notion that maximizing muscular force production per pulse may lead to improved fatigue characteristics during FES.

Nonlinear twitch force summation, the basis for N-let stimulation, is demonstrated in Fig. 3 which shows typical twitch responses to doublets at a number of different PI’s. At a PI of 200 ms, the response was simply that of two singlet twitches. At 100-ms spacing, the twitch response began to fuse and the second peak was larger than the first. As the PI was further reduced, the response fused into a single twitch whose amplitude exceeded twice that of a singlet for PI’s of 50 ms or less. The range of PI for achieving maximal, nonlinear doublet force summation as well as the magnitude of the increase in twitch force agree with prior results in the literature [11], [45].
For a PI of 2 ms, the response returned close to that of the singlet. Most likely, this is because the second pulse fell within the refractory period of most or all of the activated muscle fibers. Ruijten et al. [54] showed in experiments on the peroneal nerve of healthy human subjects that the mean relative refractory period was 0.9 ms for recovery of 5% of the axons, 1.19 ms for 50% recovery, and 1.51 ms for 95% recovery. The refractory period for muscle fibers is longer. Buchthal and Engbaek [9] found the mean absolute refractory period in isolated frog sartorius muscle fiber to be 2.5 ms for one group of frogs and 3.1 ms for another. In experiments of single muscle fiber stimulation using the brachioradialis of human subjects, Mihelin et al. [41] found the mean absolute refractory period to be 4.1 ms (minimum: 2.7 ms, maximum: 8.1 ms) for the population of 70 fibers studied.

To explore whether the nonlinear summation we observed was not due to the recruitment of additional motor units from the second pulse in the doublet, we monitored surface EMG during stimulation. Fig. 4 shows the force and EMG response to a singlet with a stimulus pulse amplitude (PA) of 40 mA, a doublet with PI = 5 ms and PA = 40 mA and a singlet with PA = 60 mA. The size of the EMG response for the doublet was approximately twice that of the 40-mA singlet, suggesting that the same motor units were being recruited twice and that the twitch forces should sum linearly. The actual doublet force, however, was nearly three times that of the singlet. Comparing the 40-mA doublet to the 60-mA singlet demonstrates that generating this force with singlet stimulation required the recruitment of additional motor units as shown by the higher EMG amplitude. Although it would be unwise to draw definitive conclusions based on EMG peak-to-peak amplitude analysis, our results do suggest that the nonlinear summation is an intrinsic property of the muscle fiber. Further, our EMG results are consistent with the more conclusive evidence of Ekle et al. [21].
Fig. 5. Set of twitch responses for one subject when stimulated with optimized N-lets. For each value of N, the PI's were sequentially optimized to produce the maximum torque-time interval. Nonlinear summation is exhibited for N = 2-6.

Fig. 6. Isometric knee torque for 5-s trains of N-let stimulation demonstrating various strategies that can be used in FES applications. The "alternating" pulse train alternates between a singlelet burst and a doublet burst with fixed N." Note the higher force production using doublet stimulation when compared to singlets at the equivalent number of pulses per second.

Because we wished to study a wide range of N-lets, we tested N-let stimulation for N in the range 1–6. Fig. 5 shows a typical set of N-let twitch responses where the PI's for each N-let were optimized. For this subject, there was nonlinear summation of amplitude for N = 2–5. From examination of the twitches normalized to their peak amplitude, there was little variation in time-to-peak or total duration of the twitch for N = 2–6.

Some example N-let stimulation strategies which could be used in FES applications are demonstrated in Fig. 6 which shows singlet, doublet, and alternating (between singlet and doublet bursts) stimulation pulse trains, all issued at the same pulse amplitude. Over the 5-s trial for this subject, a 50-pulse per second (PPS) doublet train resulted in enhanced force output when compared to a singlet train at the same 50 PPS. Also, the alternating stimulation at 37.5 PPS produced the same force as the singlet 50-PPS pulse train, but with fewer pulses. Note that the savings in number of pulses is generally accompanied by an increase in force ripple.

B. Results from Able-Bodied Subjects

Fig. 7 shows the mean and 95% confidence interval for the optimal pulse spacings within an N-let using the criteria of maximizing TTI. For N = 2–4 the data came from 27 subjects, while for N = 5–6 it came from seven subjects. For doubllets, the optimal PI was 5.09 ± 0.37 ms while for triplets, the optimal PI between the second and third pulses was 5.44±0.63 ms. Note that as N increased, the optimal PI and its variance increased.

The next N-let parameter to be determined was N, the optimal number of pulses in the burst. For reasons described previously, our criteria were to maximize the TTI per pulse of the resulting twitch. Fig. 8 shows the mean and 95% confidence interval for the normalized TTI per pulse as a function of N. Data were taken from 27 subjects for N = 1–4 and from seven subjects for N = 5–6. The TTI were normalized to that for singlets, which explains why the data for N = 1 have no variance. For all subjects, either doublet or triplet...
stimulation resulted in a higher TTI per pulse than for any other value of \( N \). Six of the subjects produced their largest TTI per pulse for doublets, nine for triplets, and the remaining 12 showed no significant difference between the two. The \( N \)-let with the highest TTI/pulse was chosen to test against singlets in the fatigue trials. When there was no significant difference between doublets and triplets, doublets were chosen, since doublet stimulation trains have lower ripple than triplet trains with the equivalent number of pulses per second.

The final parameter to be selected was the optimal \( NP \) for singlet and \( N \)-let trains (\( N = 2 \) or 3) for each subject. The performance index was based on maximizing the average torque per pulse during a continuous 5-s stimulation train, but with the constraint of less than 13% ripple. Table I displays the results of the number of times each \( NP \) was selected as optimal. Singlet data are shown for all 15 subjects in this experiment while for each subject, either a doublet or triplet data point is shown, depending on which of the two was chosen to be optimal.

The isometric torque tracking fatigue tests were conducted on 15 subjects where the performance of optimal \( N \)-let (either doublet or triplet) stimulation was compared to that of singlet stimulation. Fig. 9 displays a typical result from this test for Subject 15. The target torque was 15 Nm. Under closed-loop control, singlet stimulation was able to maintain the target torque above 75% of the target level for 36 s. With triplet stimulation, the target torque was sustained for 46 s. The lower plot shows how the pulse amplitude (PA) varied with time for each run. Note that because the triplets were able to produce more torque per pulse than the singlets, triplet stimulation required a much lower initial PA and took longer to reach the PA saturation level.

The results of torque tracking were pooled for all 15 subjects. An analysis of variance (ANOVA) test was performed with factors of subject, test order, and type of pulse train (singlet versus optimal \( N \)-let) to determine dependencies of the tracking times. The ANOVA showed that tracking times depended on subject (\( p\)-val = 0.0001) and pulse train type (\( p\)-val = 0.087), but not on test order (\( p\)-val = 0.818). For all runs, the average (mean \( \pm 95\% \) confidence interval) tracking time for singlets was 47.0 \( \pm 9.9 \) s while for optimal \( N \)-lets it was 64.1 \( \pm 23.4 \) s. A Student's \( t \)-test showed that the difference in means was significant at the 90% confidence level. Thus, on average, the optimal \( N \)-let resulted in closed-loop torque tracking that lasted 36% longer than when tracking with singlets.

Not all subjects tracked longer with the optimal \( N \)-let train. Of the 15 subjects, 12 had longer average tracking times with optimal \( N \)-lets while three had longer times with singlets. In nearly all cases, however, there was a significant difference in tracking times between the two. To demonstrate this, a second performance index was defined to augment the assessment of \( N \)-let stimulation. A tracking index (TI) was defined for each pair of successive runs (one singlet, one optimized \( N \)-let train) as the \( N \)-let time minus the singlet tracking time divided by the duration of the shorter run. Thus, \( TI = 1 \) would indicate that the optimal \( N \)-let train tracked twice as long as the singlet train while \( TI < 0 \) would indicate that singlets tracked longer. The mean TI pooled over all subjects was 0.79 \( \pm 0.79 \), again indicating that, on average, the optimal \( N \)-let outperformed the singlet. The absolute value of TI measures how much difference there was between the two stimulation paradigms, despite which tracked longer. The mean \( |TI| \) was 1.05 \( \pm 0.75 \), which indicates that, on average, one of the two pulse trains tracked for twice as long as the other.

<table>
<thead>
<tr>
<th>Singlets</th>
<th>Doublets</th>
<th>Triplets</th>
</tr>
</thead>
<tbody>
<tr>
<td>( NP )</td>
<td>Number</td>
<td>( NP )</td>
</tr>
<tr>
<td>25 ms 0</td>
<td>50 ms 5</td>
<td>48 ms 0</td>
</tr>
<tr>
<td>40 ms 10</td>
<td>80 ms 5</td>
<td>75 ms 5</td>
</tr>
<tr>
<td>55 ms 5</td>
<td>110 ms 0</td>
<td>111 ms 5</td>
</tr>
<tr>
<td>75 ms 5</td>
<td>140 ms 0</td>
<td>150 ms 0</td>
</tr>
</tbody>
</table>
C. Results from SCI Subjects

In general, the results from the four SCI subjects were similar to those from the 27 able-bodied subjects. The average optimal PI for doublets was 4.5 ms (the four data points were 4, 4, 6, and 4), while the average optimal spacing between the second and third pulses of the triplet was 8.0 ms (data points were 4, 8, 12, and 8). All four subjects indicated doublets to be the optimal N. The optimal NP varied among the subjects and for singlets the preferences were 55, 40, 70, and 25 ms, while for doublets they were 80 ms for two subjects and 50 and 110 ms for the remaining two.

The torque tracking protocol was performed on two of the four SCI subjects. The tracking indices (TI) were −0.26 and 0.28 for the trials where the singlet was tested first, and 0.07 and 1.95 for the trials where the doublet was tested first. The average TI was 0.51 indicating that, on average, optimal N-lets tracked for 51% longer.

IV. DISCUSSION

The objective of this work was to test the hypothesis that stimulation by optimal N-let pulse trains reduces muscle fatigue during FES. The results demonstrate that the hypothesis is true since, on average, torque tracking with N-lets was 36% longer than with singlets. Furthermore, the tracking index results indicated that there was almost always a significant difference between the performance with singlets and that with optimal N-lets. There was considerable intersubject variation in the choice of optimal N-let parameters. For example, in three of 15 able-bodied cases, singlets consistently produced longer torque tracking times. Thus, when considering the use of N-let stimulation in FES applications, preliminary testing should be performed to determine which stimulation paradigm produces the most fatigue resistant contractions.

There were no major differences between the results from SCI subjects and the results from able-bodied subjects, however, the data from the SCI subjects exhibited higher variability than the data from able-bodied subjects, possibly because it was difficult for the SCI subjects to remain seated in one position for the tracking trials spaced by the 15-min rest period. Demonstrating that optimal N-let stimulation can provide for improved torque tracking in SCI subjects was important because it would be inappropriate to make a priori assumptions about whether chronically stimulated muscle fibers exhibit nonlinear force summation. Our four SCI subjects spanned the range of what one would expect to see in a clinical FES-aided standing or gait program in terms of their training. One had exercised his quadriceps via electrical stimulation daily for nearly three years while the other three had from six to twelve months of stimulation. Using this subject pool to show the efficacy of N-let stimulation demonstrates its potential utility in FES applications.

The comparison between singlets and N-lets was influenced by the choice of NP for the torque tracking tests. We had a specific criteria for selecting the optimal NP based on maximizing torque per pulse with acceptable ripple. Ideally, the torque tracking trials should be performed with several different NPs because we did not test the assumption that there is a direct link between maximum average torque per pulse in short contractions and fatigue resistance in long contractions. A second method for choosing the optimal NP would be to equate the total number of pulses per second for the singlet train with that for the optimal N-let train. For example, if stimulating with a singlet train of \( NP = 25 \) ms, the equivalent doublet train would be at \( NP = 50 \) ms. In preliminary experiments, this method of testing usually led to the doublet train tracking longer. A third method for choosing the optimal NP would be to pick an initial NP which gave the same force as the singlet train at the same PA, and then increase NP until the ripple reached 13%. A fourth method would be to set NP for doublets equal to that for singlets. This would insure that doublet torque tracking could be done at a PA that was initially lower than that for singlets, thus providing more room for increasing PA in the closed-loop tracking controller. We did not test either of the last two methods, but it is clear that choosing the best value of NP is a complex problem which deserves detailed study.

The results for optimal values of PI for N-let twitch stimulation with \( N = 1\)–6 agree with prior studies that the length of the first interval should be around 5 ms to maximize the TTI [11], [21], [45], [58], [59], [62]. There is disagreement on the later intervals, however, since the prior studies suggested the optimal interval is around 100 ms while we found 6 to 8 ms to be optimal. This may have been because we limited our search to PI’s of less than 20 ms to produce a single fused twitch. Optimal values for PI will also change depending on the fiber composition of the muscle being stimulated. N-let bursts with large N and longer PT’s approach the case of continuous stimulation whereas the CNS is known to optimize muscle activity with an initial burst followed by a slowing of firing rate [17]. Clearly, more can be done in FES applications to mimic the CNS by tailoring stimulation patterns for particular motions.

A complementary study by Franken et al. supports part of our results [24]. They compared doublet and triplet stimulation to singlet stimulation in both brief and fatiguing contractions. The PI’s for the N-lets were fixed at 10 ms. Their results showed that triplets had some advantage in improving the TTI per pulse. The differences, however, were not dramatic, possibly because the study did not investigate optimizing PI.

In this study, we limited our scope to continuous isometric contractions and make no claims for the suitability of N-let stimulation for rapid motions or for tracking complex torque trajectories with wide dynamic range and bandwidth, although we suspect that these would also benefit from N-let stimulation. Nevertheless, there is still considerable utility in the results because many FES applications involve simple isometric contractions. FES-aided standing presents a good example since the goal is to produce a nonfatiguing contraction of the quadriceps muscle with the knee joint fixed. Even in FES-aided gait, much of the time is spent in the double-support phase with the knee joints locked through stimulation. Likewise, in FES-aided grasp, fatigue-resistant isometric contractions are required for maintaining a long-term grip of an object such as an eating utensil. Nevertheless, it would be useful to conduct additional studies of N-let stimulation
under nonisometric conditions and for muscles other than the quadriceps.

Although not tested, it is likely that N-let stimulation will prove to be effective with implanted FES systems as well as with surface stimulation because the nonlinear twitch force summation is a property of the muscle fiber rather than one of axonal recruitment. Thus, it should be possible to obtain improved fatigue resistance with N-let stimulation using intramuscular and nerve cuff electrodes as well as with surface electrodes.

Ideally, comparison tests between singlets and optimal N-lets as well as comparison PI testing should be done on a subject by subject basis to determine optimal stimulation parameters. If impractical, two recommendations for FES applications can be made based on the results of this research. First, we found the "best" stimulation train to be doubles with a spacing between the two pulses in the burst of about 5 ms. Doubles are recommended because even in those cases where triplets resulted in optimal performance, doubles were near optimal. Second, NP should be chosen to be as large as possible while still maintaining acceptable force ripple in the contractions.

V. CONCLUSIONS

Nonlinear force summation for closely spaced N-let stimulation is exhibited for surface stimulation of human quadriceps muscle and this property of muscle fibers can be exploited beneficially in FES applications. There is considerable subject-to-subject variation in the results, but specific recommendations can be made for generic "optimal" stimulation pulse train parameters which will minimize fatigue. A double stimulation strategy is relatively easy to implement and can be incorporated into FES equipment with little difficulty. The strategy can also be combined with other fatigue-reducing approaches such as cyclical or natural size-order stimulation. Thus, there is great potential for minimizing fatigue in practical FES applications by simply modifying the stimulation patterns.

ACKNOWLEDGMENT

The work of this paper was conducted in the Eric P. and Evelyn E. Newman Laboratory for Biomechanics at MIT with additional experiments taking place at the VA Medical Center, West Roxbury, MA.

REFERENCES


Zoher Z. Karu (S’92) was born in Bombay, India in 1968. He received the B.S. degree in electrical engineering from Carnegie Mellon University, Pittsburgh, PA, in 1990, followed by the M.S. degree in electrical engineering in 1992 from the Massachusetts Institute of Technology, Cambridge, MA, for his thesis in the area of functional electrical stimulation. During the summer of 1992, he was an ONR Research Fellow at the Naval Health Research Center in San Diego, CA, working in the area of quantifying and classifying EMG patterns for clinical use. He is currently pursuing the Ph.D. in electrical engineering at MIT under the supervision of Dr. T. Weiss and Dr. D. Freeman.

His research concerns motion detection and estimation of live hair cells in the inner ear as captured through video microscopy. As a graduate student, he authored Signals and Systems Made Ridiculously Simple published by Ziti Press (Cambridge, MA), a company that he started in 1994.

Mr. Karu is a recipient of the National Engineering Consortium’s Student Award of Excellence and is also a Member of Tau Beta Pi andEta Kappa Nu.

William K. Durfee (S’79–M’85) received the B.S. and Ph.D. degrees in mechanical engineering from the Massachusetts Institute of Technology in 1981 and 1985, respectively.

From 1983 until 1993, he was first Assistant and then Associate Professor of Mechanical Engineering at MIT. During the last two years, he was the Brit and Alex d’Arbeloff Associate Professor of Engineering Design. Since 1993, he has been with the Department of Mechanical Engineering at the University of Minnesota where he holds the title of Associate Professor and Director of Design Education. His research interests include design and applied controls, biomechanics and neuromuscular physiology of human movement, and the design and development of assistive technology which makes use of functional electrical stimulation. He also conducts research in product prototyping and is extensively involved in the design education program at the University of Minnesota.

Aaron M. Barzilai received the B.S. in mechanical engineering from the Massachusetts Institute of Technology in 1990. Currently, he is a graduate student at Stanford University where he earned the M.S. in mechanical engineering in 1995 and is now working toward the Ph.D.

His research involves the development of micro-electromechanical sensors based on the tunneling effect. Other interests include mechatronic design and control systems.