COMPARING THE FORCE RIPPLE DURING ASYNCHRONOUS AND CONVENTIONAL STIMULATION

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ABSTRACT: *Introduction*: Asynchronous stimulation has been shown to reduce fatigue during electrical stimulation; however, it may also exhibit a force ripple. We quantified the ripple during asynchronous and conventional single-channel transcutaneous stimulation across a range of stimulation frequencies. *Methods*: The ripple was measured during 5 asynchronous stimulation protocols, 2 conventional stimulation protocols, and 3 volitional contractions in 12 healthy individuals. *Results*: Conventional 40 Hz and asynchronous 16 Hz stimulation were found to induce contractions that were as smooth as volitional contractions. Asynchronous 8, 10, and 12 Hz stimulation induced contractions with significant ripple. *Conclusions*: Lower stimulation frequencies can reduce fatigue; however, they may also lead to increased ripple. Future efforts should study the relationship between force ripple and the smoothness of the evoked movements in addition to the relationship between stimulation frequency and NMES-induced fatigue to elucidate an optimal stimulation frequency for asynchronous stimulation.

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Neuromuscular electrical stimulation (NMES) is used commonly in rehabilitation settings where the goal is to increase muscle size, strength, and function[1–4] and may also be used to produce functional tasks (e.g., standing, stepping, reaching, grasping, cycling)[5–9] where it is termed functional electrical stimulation (FES). One potential limitation to FES is NMES-induced fatigue. In FES applications, maximal power generation and muscle stamina are still major causes of concern.[9] Fatigue limits the potential duration that a desired task can be performed, and thus, methods are sought to reduce NMES-induced fatigue.[10–14]

One suggested cause of NMES-induced fatigue is nonselective, spatially fixed, synchronous recruitment of motor units during conventional stimulation.[15,16] Due to temporal summation of muscle force, higher stimulation frequencies are required to achieve smooth force output when motor units are recruited synchronously rather than asynchronously. Higher stimulation frequencies are associated with increased rates of fatigue,[11,17–20] and thus, when the goal is to minimize fatigue or sustain a desired functional outcome, low stimulation frequencies should be used.

Researchers have examined 2 methods to reduce fatigue during NMES based on the principle of using multiple stimulation channels to reduce the average stimulation frequency in each channel. The first method is sequential stimulation (also described in previous literature as alternating,[21] cyclical,[22] or sequential segmental stimulation[23,24]). During sequential stimulation, multiple stimulation channels are used to target multiple synergistic muscles[21,22] or multiple segments of a single muscle.[23,24] Pulse trains are then delivered sequentially to each stimulation channel in an effort to reduce the duty cycle of the targeted muscles or muscle segments. A potential limitation to using sequential stimulation during FES is that there may be discrete jumps in force production when switching stimulation channels due to the fact that each stimulation channel is likely to elicit differing force responses to the same stimulus.

A similar and more commonly used method to reduce fatigue is asynchronous stimulation (also described in previous literature as rotary,[25] distributed,[26–29] interleaved,[19,20,30,31] sequential,[32] or spatially distributed sequential stimulation[33]). Similar to sequential stimulation, asynchronous stimulation uses multiple stimulation channels to target multiple synergistic muscles or different segments of a single muscle. However, during asynchronous stimulation, the stimulus pulses are delivered in an interleaved manner (i.e., switching the active stimulation channel following each individual pulse rather than after each pulse train). Thus, while sequential stimulation may result in discrete jumps in the force response, asynchronous stimulation exhibits an averaging effect due to the temporal summation of the individual force responses. However, asynchronous stimulation may still exhibit a ripple in the force output. A force ripple is characterized by contractions that are not fully fused, thus exhibiting force tracings (or equivalently, torque tracings) which are not smooth. Ripple can be reduced by increases in stimulation frequency; however, lower stimulation frequencies should be

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Abbreviations: FES, functional electrical stimulation; LEM, leg extension machine; MVC, maximal voluntary contraction; NMES, neuromuscular electrical stimulation; RMS, root mean square

Key words: asynchronous stimulation; force ripple; functional electrical stimulation; muscle fatigue; neuromuscular electrical stimulation; torque ripple

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used, because high stimulation frequencies induce fatigue more quickly than low frequencies.[11,17–20]

While previous research has examined the effectiveness of asynchronous stimulation as a method to reduce fatigue,[19,20,26–28,30,32–35] few results have examined force ripple with asynchronous stimulation.[19,20,25,29] Hughes et al.[20] studied epimysial stimulation of the plantaris longus muscle in frogs. The authors found that asynchronous stimulation with 4 channels at 15 Hz (resulting in a composite frequency equivalent to 60 Hz single-channel stimulation) produced less ripple than conventional (i.e., synchronous) single-channel stimulation at 15 Hz while producing more ripple than conventional single-channel 60 Hz stimulation. Similarly, McDonnall et al.[19] studied asynchronous intrafascicular stimulation of the sciatic nerve in cats and reported that 15 Hz stimulation with 4 channels (resulting in a composite frequency equivalent to 60 Hz single-channel stimulation) resulted in less ripple than conventional single-channel stimulation at 15 Hz. Lind and Petrofsky[25] studied asynchronous stimulation through surgically divided groups of ventral roots in cats, targeting the plantaris, medial gastrocnemius, and soleus. They showed that asynchronous stimulation of 10 Hz with 3, 5, and 10 channels (composite frequencies of 30, 50, and 100 Hz) produced smoother contractions, greater tension, and a faster rate of tension rise than conventional single-channel stimulation at 10 Hz. Furthermore, as the number of channels was increased, thereby increasing the composite frequency, the tension increased in amplitude and became smoother. They also examined the tension developed during asynchronous stimulation with 3, 5, and 10 stimulation channels at various stimulation frequencies and found that maximal tetanic tensions were always reached at a lower frequency with asynchronous stimulation than with conventional single-channel stimulation, but force ripple was not quantified. Brown et al.[29] studied asynchronous stimulation of the soleus and medial gastrocnemius in cats by activating the muscle through cut ventral roots with 6 channels of stimulation. They compared the force ripple during asynchronous stimulation at multiple stimulation frequencies where the pulses were delivered with equal time intervals or with unequal time intervals in an attempt to reduce the ripple. They found that shifting the stimulus times could reduce the ripple.

The aim of this study was to quantify and compare isometric force ripple (or equivalently, torque ripple) during asynchronous and conventional single-channel stimulation with surface electrodes across a range of stimulation frequencies in healthy individuals. We expected that force ripple could be decreased by using higher stimulation frequencies; however, lower stimulation frequencies are preferred to reduce NMES-induced fatigue. Thus, knowledge of the interplay between stimulation frequency and force ripple may guide the choice of stimulation frequency during asynchronous FES.

MATERIALS AND METHODS

Twelve healthy individuals (age 28.5 ± 7.5 years) participated in the study. Before participation, written informed consent was obtained from each individual, as approved by the institutional review board at the University of Florida. Individuals were asked to sit in a modified leg extension machine (LEM). The LEM allows for seating adjustments such that the axis of rotation of the knee joint could be aligned with the axis of rotation of the LEM. The LEM was fitted with a force transducer such that the isometric knee-joint torque could be measured. Isometric torque was recorded during 5 asynchronous stimulation protocols with stimulation frequencies ranging from 8 to 16 Hz in 2 Hz steps as well as during 2 conventional (i.e., synchronous) single-channel stimulation protocols with stimulation frequencies of 20 and 40 Hz. Isometric torque was also acquired during volitional contractions to provide a reference for the smoothness of volitional contractions in healthy individuals. As stated previously, a force ripple is characterized by contractions that are not fully fused, thus exhibiting force tracings (or equivalently, torque tracings) which are not smooth. Recorded isometric torque measurements from a single individual are shown in Figure 1 to better illustrate the difference between smooth contractions and those which exhibit a ripple. The root mean square (RMS) ripple was computed for each volitional and NMES-induced contraction, expressed as a percentage of the mean torque.

Stimulation pulses were delivered by a current-controlled 8-channel stimulator (RehaStim, Hasomed GmbH, Germany), which was controlled by a personal computer. Conventional stimulation consisted of a single stimulation channel with a pair of surface electrodes placed over the quadriceps femoris muscle, while asynchronous stimulation consisted of 4 channels of stimulation. For asynchronous stimulation, the stimulation pulses were interleaved across the stimulation channels. In other words, asynchronous stimulation of 10 Hz with 4 channels results in a composite stimulation frequency of 40 Hz. The electrode configuration used during asynchronous stimulation is depicted in Figure 2, and the method of interleaving the pulses across the stimulation channels is depicted in Figure 3.

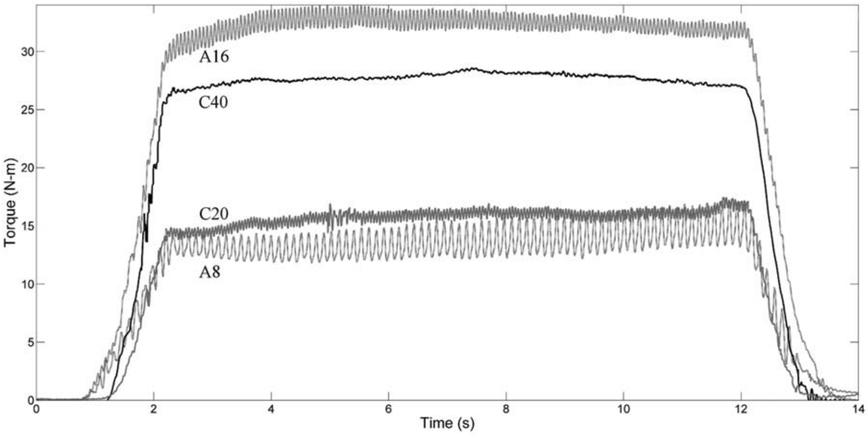

FIGURE 1. Example isometric torque measurements acquired from a single individual which illustrates the presence of ripple (i.e., contractions exhibiting force tracings which are not smooth) during asynchronous stimulation. A16 and A8 refer to asynchronous multi-channel stimulation of 16 and 8 Hz, respectively. C40 and C20 refer to conventional single-channel stimulation of 40 and 20 Hz, respectively. In this example, A16, C40, C20, and A8 evoked mean torques of 32.4, 27.8, 16.1, and 14.1 N-m, respectively.

At the beginning of each experiment, each individual was asked to perform a maximal voluntary contraction (MVC) while the isometric torque was recorded. The individual was then asked to perform contractions at 50% and subsequently 25% of his or her MVC. To aid the individual's ability to reach the desired torque, visual feedback of the torque was provided by means of a display. The individual then received asynchronous 16 Hz stimulation, while the current amplitude was slowly incremented. This served as a warm-up session while also providing a guideline to select the desired current amplitude. For each individual, the desired current amplitude was selected as either the current amplitude which evoked a contraction of at least 20% of the MVC or the current amplitude beyond which increases in current amplitude caused discomfort, whichever occurred first. Due to subject discomfort, 20% of the MVC was not always obtained during the warm-up session with asynchronous 16 Hz stimulation. The mean current amplitude selected for each individual was 39.7 ± 10.1 mA.

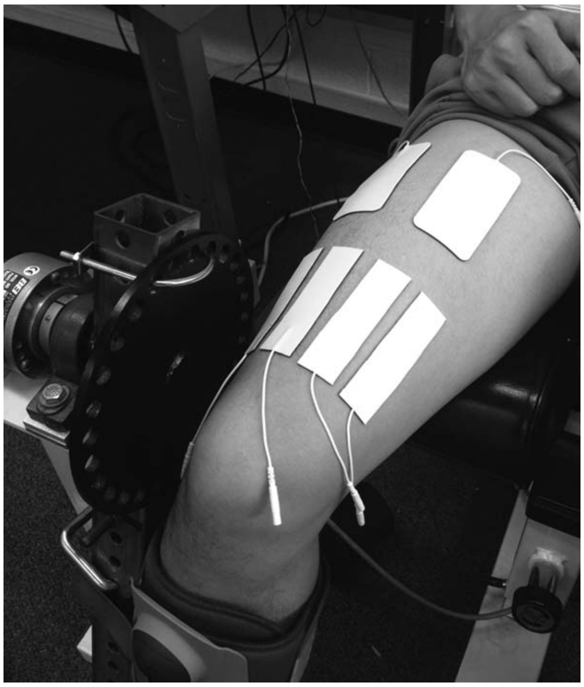

FIGURE 2. Electrode configuration for asynchronous stimulation with 2 electrodes placed proximally and 4 electrodes placed distally. The stimulation channels corresponding to the 2 most medial distal electrodes share the most medial proximal electrode, while the stimulation channels corresponding to the 2 most lateral distal electrodes share the most lateral proximal electrode. A force transducer was fixed to the leg extension machine to acquire the isometric torque.

The ripple present during asynchronous and conventional stimulation was then examined by delivering biphasic pulses with a pulsewidth of 350 μs and the desired current amplitude previously determined in the warm-up session. While it is possible to adjust the current amplitude for each

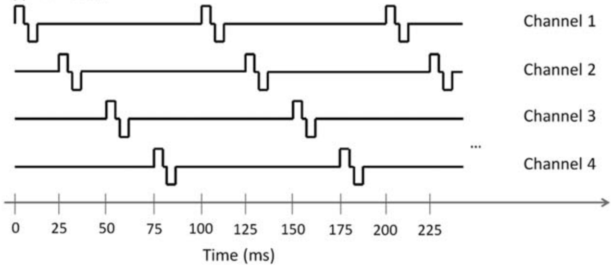

FIGURE 3. During asynchronous stimulation, multiple channels are used where high composite stimulation frequencies are achieved by interleaving the pulses. Depicted is asynchronous 10 Hz stimulation with 4 channels where each channel receives pulse trains at 10 Hz, but the composite stimulation frequency is 40 Hz. Note that the width of the pulses is not drawn to scale for illustrative purposes.

Table 1. RMS ripple expressed as a percentage of mean torque.*

	RMS Ripple (%DC)									
	Protocol									
Subject	A16	A14	A12	A10	A8	C40	C20	V100	V50	V25
A	2.43	3.68	4.49	3.89	9.61	0.33	4.55	0.82	2.67	1.15
B	0.30	0.95	2.85	6.95	8.29	0.64	1.06	0.94	1.28	0.92
C	0.46	1.72	3.95	3.04	4.01	0.44	1.73	1.12	1.28	0.54
D	1.09	5.62	14.36	7.44	4.86	0.30	3.04	1.79	1.56	0.75
E	1.65	4.18	6.43	7.05	8.42	0.21	1.97	1.53	0.39	0.27
F	0.56	1.51	12.77	6.88	9.30	0.45	1.12	0.78	0.63	0.55
G	0.99	5.09	4.79	7.21	18.07	0.57	4.33	0.50	0.73	0.41
H	2.15	4.98	9.54	13.03	13.08	1.42	5.11	1.22	0.57	0.44
I	1.29	1.45	2.51	1.45	4.82	0.41	4.02	0.98	0.57	0.66
J	0.94	0.59	6.89	4.00	8.28	0.32	1.91	1.11	0.63	0.40
K	0.46	1.94	5.80	7.84	8.90	1.30	1.47	1.44	1.46	0.62
L	0.43	0.45	6.84	3.69	6.01	0.58	1.81	1.17	1.65	0.50
Mean	1.06	2.68	6.77	6.04	8.64	0.58	2.68	1.12	1.12	0.60
SD	0.70	1.90	3.73	3.05	3.90	0.39	1.46	0.35	0.66	0.24

**A16, A14, A12, A10, and A8 refer to asynchronous 16, 14, 12, 10, and 8 Hz stimulation, respectively. C40 and C20 refer to conventional 40 and 20 Hz stimulation, respectively. V100, V50, and V25 refer to volitional contractions at 100%, 50%, and 25% of the maximal voluntary contraction, respectively.*

protocol in an effort to match the mean torque output, doing so may induce fatigue. Therefore, to provide a fair comparison of protocols while minimizing the effect of fatigue, the ripple was quantified as a percentage of mean torque. For subject comfort, the current amplitude was increased as a ramp from 0 mA to the desired amplitude over the course of 2 s. The current amplitude then remained constant for 10 s before decreasing back to 0 mA over the course of 2 s. The duration of constant stimulation was chosen as 10 seconds in an effort to reduce potential fatigue; however, the duration was sufficiently long so that the ripple could be measured. To further reduce any effect of fatigue, the order of stimulation protocols was randomized for each individual, and the individuals were allowed to rest for a minimum of 2 min between each trial. A simple linear regression was performed with the protocol order as the independent variable and the mean torque output as the dependent variable in an effort to examine whether or not fatigue occurred throughout the trials. Because conventional and asynchronous stimulation use different electrode configurations and the protocol order was randomized, the electrode positions were marked so that the positioning could be replicated when placing and removing the electrodes.

RESULTS

Isometric knee-joint torque was recorded during 5 asynchronous stimulation protocols with stimulation frequencies of 8, 10, 12, 14, and 16 Hz (subsequently described as A8, A10, A12, A14, and A16) as well as during 2 conventional single-channel stimulation protocols with stimulation frequencies of 20 and 40 Hz (subsequently described as C20 and C40). Isometric torque was also acquired during volitional contractions at 100%, 50%, and 25% of each individual's MVC (subsequently described as V100, V50, and V25). The RMS values of the ripple measured during volitional and NMES-induced contractions are listed in Table 1, and the corresponding box plot is shown in Figure 4. Higher stimulation frequencies resulted in less ripple during asynchronous stimulation than low stimulation frequencies. The 2 asynchronous stimulation protocols with the

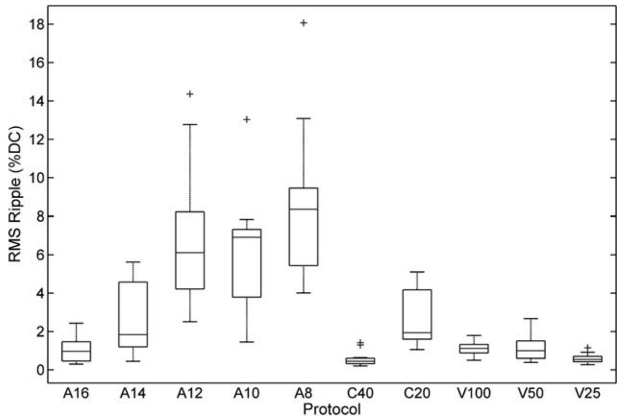

FIGURE 4. Box plot of the RMS value of the ripple expressed as a percentage of the mean torque produced. The central marks in the boxes represent the median, the edges of the boxes represent the 25th and 75th percentiles, and the whiskers extend to the most extreme data points not considered to be outliers, as the outliers are plotted separately as plus signs. A16, A14, A12, A10, and A8 refer to asynchronous 16, 14, 12, 10, and 8 Hz stimulation, respectively. C40 and C20 refer to conventional 40 and 20 Hz stimulation, respectively. V100, V50, and V25 refer to volitional contractions at 100%, 50%, and 25% of the maximal voluntary contraction, respectively.

Table 2. Mean torque (N-m) produced by each stimulation protocol.*

	Mean Isometric Torque (N-m)						
	Stimulation Protocol						
Subject	A16	A14	A12	A10	A8	C40	C20
A	24.2	23.8	21.3	20.8	10.4	22.1	15.2
B	33.2	32.6	31.9	18.1	9.9	6.3	6.1
C	19.2	21.1	16.7	17.7	13.4	18.9	19.0
D	27.8	31.4	18.4	24.5	18.9	24.7	11.7
E	32.4	31.4	27.6	23.5	14.1	27.8	16.1
F	20.2	18.3	14.7	11.3	6.5	11.3	8.4
G	28.3	17.6	18.7	10.1	7.5	7.0	4.5
H	25.8	25.1	16.3	12.3	6.9	6.6	5.7
I	38.6	39.5	35.2	37.7	16.4	19.1	22.9
J	48.6	43.7	42.4	38.0	22.5	36.2	20.6
K	48.6	36.6	34.5	26.7	22.6	4.9	17.4
L	60.5	63.8	46.0	43.3	21.8	16.5	12.8
Mean	33.9	32.1	27.0	23.7	14.2	16.8	13.4
SD	12.8	13.0	10.8	11.0	6.1	9.9	6.2

**A16, A14, A12, A10, and A8 refer to asynchronous 16, 14, 12, 10, and 8 Hz stimulation, respectively. C40 and C20 refer to conventional 40 and 20 Hz stimulation, respectively.*

highest stimulation frequencies (A16 and A14) were found to induce contractions with mean RMS ripple values of 1.06%, and 2.68%, respectively. Meanwhile, the 3 asynchronous protocols with the lowest stimulation frequencies (A12, A10, and A8) were found to induce contractions with mean RMS ripple values of 6.77%, 6.04%, and 8.64%, respectively.

The mean torque evoked during each stimulation protocol is listed in Table 2. Asynchronous stimulation was found to produce stronger contractions on average, with mean torques of 33.9, 32.1, 27.0, 23.7, and 14.2 N-m for A16, A14, A12, A10, and A8, respectively. Meanwhile, conventional stimulation produced generally weaker contractions, with mean torques of 16.8 and 13.4 N-m for C40 and C20, respectively. To examine if fatigue due to protocol order affected the data, a simple linear regression was performed with the protocol order as the independent variable and the mean torque output as the dependent variable. While the linear regression resulted in a linear curve fit with a downward slope, regression analysis resulted in a *P*-value of 0.0596. Thus, there is not enough evidence to conclude that there is a relationship between the protocol order and the mean torque at a significance level of $\alpha = 0.05$. While we cannot exclude the possibility that some fatigue occurred with the order of contractions, the coefficient of determination was found to be 0.0426, further indicating that the protocol order explained less than 5% of the variation in torque. The linear fit to the evoked torque as a function of the protocol order is shown in Figure 5.

DISCUSSION

The results indicate that both asynchronous 16 Hz stimulation and conventional 40 Hz stimulation can induce contractions which are as ripple-free as volitional contractions in healthy individuals (see Fig. 4 and Table 1). However, on average, asynchronous 16 Hz stimulation induced contractions that were more than twice as strong as conventional 40 Hz stimulation, given the same current amplitude (see Table 2). Asynchronous 16 Hz stimulation with 4 channels has been shown previously to induce less fatigue than conventional 40 Hz stimulation.[34] Thus, when smooth, strong, fatigue-resistant contractions are desired, asynchronous 16 Hz stimulation is preferred over conventional 40 Hz stimulation.

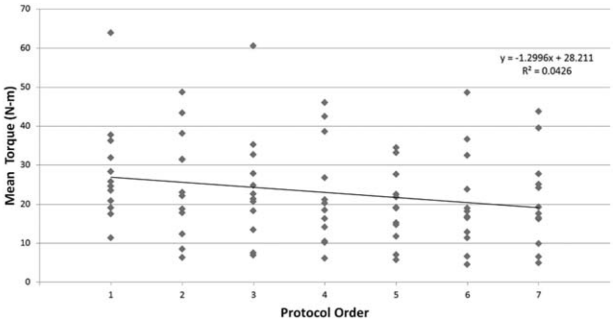

FIGURE 5. Scatter plot of the mean torque produced as a function of the protocol order with the corresponding linear fit. While the linear regression resulted in a linear curve fit with a downward slope, regression analysis resulted in a *P*-value of 0.0596. Thus, there is not enough evidence to conclude that there is a relationship between the protocol order and the mean torque at a significance level of $\alpha = 0.05$. Furthermore, the coefficient of determination was found to be 0.0426, indicating that the protocol order explained less than 5% of the variation in torque.

Asynchronous 14 Hz stimulation induced contractions with similar ripple to that of conventional 20 Hz stimulation; however, neither protocol was as ripple-free as volitional contractions (see Fig. 4 and Table 1). On average, asynchronous 14 Hz stimulation induced contractions that were more than twice as strong as conventional 20 Hz stimulation, given the same current amplitude (see Table 2). While it is expected that asynchronous 14 Hz stimulation would induce less fatigue than conventional 20 Hz stimulation, previous studies have not compared the NMES-induced fatigue of the 2 protocols. Thus, it is not presently clear if asynchronous 14 Hz stimulation provides a significant fatigue benefit over conventional 20 Hz stimulation, in addition to producing stronger contractions.

Asynchronous 10 Hz stimulation was found to induce 40% stronger contractions than conventional 40 Hz stimulation on average, given the same current amplitude (see Table 2). This result is in agreement with previous findings, where asynchronous 10 Hz stimulation required 20% less current to reach the same desired torque.[33] Asynchronous 10 Hz stimulation has been shown previously to induce less fatigue than conventional 40 Hz stimulation,[26,33] and thus, asynchronous 10 Hz stimulation would be the preferred FES protocol if it exhibited similar ripple to conventional 40 Hz stimulation. In theory, asynchronous 10 Hz stimulation with 4 channels is capable of eliciting contractions which are as smooth as conventional 40 Hz stimulation; however, the results indicate that asynchronous 10 Hz stimulation may exhibit significantly more ripple than conventional 40 Hz stimulation (see Fig. 4 and Table 1). Furthermore, the 3 asynchronous stimulation protocols with the lowest stimulation frequencies (8, 10, and 12 Hz) were found to produce significant ripple compared with volitional contractions (see Fig. 4 and Table 1). While these 3 protocols are expected to reduce NMES-induced fatigue, the results suggest that 8, 10, and 12 Hz asynchronous stimulation with 4 channels may not be suitable for FES applications that require contractions which are as smooth as volitional contractions in healthy individuals.

It should be noted that different electrode configurations (i.e., electrode size, shape, placement, and the number of stimulation channels) could alter the amount of ripple during asynchronous stimulation. However, the electrode configuration of this study was selected in an effort to prevent activation overlap which could otherwise limit the effectiveness of asynchronous stimulation as a method to reduce fatigue. Low stimulation frequencies have been shown to reduce fatigue, but this study indicates that low frequency asynchronous stimulation can lead to increased ripple. Thus, future research should investigate methods to reduce ripple so that low frequency asynchronous stimulation may produce strong, smooth, and fatigue-resistant contractions.

The extent that force ripple impacts FES control and the smoothness of FES-induced movement remains an unanswered question. We investigated force ripple during volitional contractions of healthy individuals under the assumption that stimulation protocols resulting in a similar amount of force ripple are sufficient to produce movements similar to that of healthy individuals. However, because the relationship between isometric force ripple and the smoothness of FES-induced movement is not presently known, future studies should investigate this relationship to determine the lowest suitable stimulation frequency to elicit movements similar to that of healthy individuals. Future efforts should also examine the relationship between stimulation frequency and NMES-induced fatigue during asynchronous stimulation. Low stimulation frequencies have been shown to reduce NMES-induced fatigue; however, there may be a lower bound on the stimulation frequency beyond which there is no discernible change in NMES-induced fatigue. Thus, the choice of an optimal asynchronous stimulation frequency that elicits fatigue-resistant movements similar to the volitional movements of healthy individuals is a topic of interest for future studies on NMES-induced fatigue and the effect of force ripple on the FES-induced movement.

REFERENCES

1. Sabut SK, Sikdar C, Mondal R, Kumar R, Mahadevappa M. Restoration of gait and motor recovery by functional electrical stimulation therapy in persons with stroke. Disabil Rehabil 2010;32:1594–1603.
2. Yan T, Hui-Chan CWY, Li LSW. Functional electrical stimulation improves motor recovery of the lower extremity and walking ability of subjects with first acute stroke: a randomized placebo-controlled trial. Stroke 2005;36:80–85.
3. Stackhouse SK, Binder-Macleod SA, Stackhouse CA, McCarthy JJ, Prosser LA, Lee SCK. Neuromuscular electrical stimulation versus volitional isometric strength training in children with spastic diplegic cerebral palsy: a preliminary study. Neurorehabil Neural Repair 2007; 21:475–485.
4. Snyder-Mackler L, Delitto A, Stralka SW, Bailey SL. Use of electrical stimulation to enhance recovery of quadriceps femoris muscle force production in patients following anterior cruciate ligament reconstruction. Phys Ther 1994;74:901–907.
5. Kesar TM, Perumal R, Reisman DS, Jancosko A, Rudolph KS, Higginson JS, et al. Functional electrical stimulation of ankle plantarflexor and dorsiflexor muscles: effects on poststroke gait. Stroke 2009;40:3821–3827.
6. Sabut SK, Lenka PK, Kumar R, Mahadevappa M. Effect of functional electrical stimulation on the effort and walking speed, surface electromyography activity, and metabolic responses in stroke subjects. J Electromyogr Kinesiol 2010;20:1170–1177.
7. Ferrante S, Ambrosini E, Ferrigno G, Pedrocchi A. Biomimetic NMES controller for arm movements supported by a passive exoskeleton. Proc IEEE Eng Med Biol Soc 2012;1888–1891.
8. Prochazka A, Gauthier M, Wieler M, Kenwell Z. The bionic glove: an electrical stimulator garment that provides controlled grasp and hand opening in quadriplegia. Arch Phys Med Rehabil 1997;78:608–614.
9. Duffell LD, Donaldson NN, Newham DJ. Power output during functional electrically stimulated cycling in trained spinal cord injured people. Neuromodulation 2010;13:50–57.

10. Downey RJ, Bellman M, Sharma N, Wang Q, Gregory CM, Dixon WE. A novel modulation strategy to increase stimulation duration in neuromuscular electrical stimulation. Muscle Nerve 2011;44:382–387.
11. Gregory CM, Dixon WE, Bickel CS. Impact of varying pulse frequency and duration on muscle torque production and fatigue. Muscle Nerve 2007;35:504–509.
12. Doucet BM, Griffin L. Maximal versus submaximal intensity stimulation with variable patterns. Muscle Nerve 2008;37:770–777.
13. Karu ZZ, Durfee WK, Barzilai AM. Reducing muscle fatigue in FES applications by stimulating with N-let pulse trains. IEEE Trans Biomed Eng 1995;42:809–817.
14. Binder-Macleod SA, Lee SCK, Baadte SA. Reduction of the fatigue induced force decline in human skeletal muscle by optimized stimulation trains. Arch Phys Med Rehabil 1997;78:1129–1137.
15. Bickel CS, Gregory CM, Dean JC. Motor unit recruitment during neuromuscular electrical stimulation: a critical appraisal. Eur J Appl Physiol 2011;111:2399–2407.
16. Gregory CM, Bickel CS. Recruitment patterns in human skeletal muscle during electrical stimulation. Phys Ther 2005;85:358–364.
17. Binder-Macleod SA, Halden EE, Jungles KA. Effects of stimulation intensity on the physiological responses of human motor units. Med Sci Sports Exerc 1995;27:556–565.
18. Jones DA, Bigland-Ritchie B, Edwards RHT. Excitation frequency and muscle fatigue: mechanical responses during voluntary and stimulated contractions. Exp Neurol 1979;64:401–413.
19. McDonnall D, Clark GA, Normann RA. Interleaved, multisite electrical stimulation of cat sciatic nerve produces fatigue-resistant, ripple-free motor responses. IEEE Trans Neural Syst Rehabil Eng 2004;12: 208–215.
20. Hughes AC, Guo L, DeWeerth SP. Interleaved multichannel epimysial stimulation for eliciting smooth contraction of muscle with reduced fatigue. Proc IEEE Eng Med Biol Soc 2010;2010:6226–6229.
21. Decker MJ, Griffin L, Abraham LD, Brandt L. Alternating stimulation of synergistic muscles during functional electrical stimulation cycling improves endurance in persons with spinal cord injury. J Electromyogr Kinesiol 2010;20:1163–1169.
22. Pournezam M, Andrews BJ, Baxendale RH, Phillips GF, Paul JP. Reduction of muscle fatigue in man by cyclical stimulation. J Biomed Eng 1988;10:196–200.
23. Zonnevijlle ED, Somia NN, Stremel RW, Maldonado CJ, Werker PM, Kon M, et al. Sequential segmental neuromuscular stimulation: an effective approach to enhance fatigue resistance. Plast Reconstr Surg 2000;105:667–673.
24. Stremel RW, Zonnevijlle EDH. Re-animation of muscle flaps for improved function in dynamic myoplasty. Microsurgery 2001;21:281–286.
25. Lind AR, Scott Petrofsky J. Isometric tension from rotary stimulation of fast and slow cat muscles. Muscle Nerve 1978;1:213–218.
26. Maneski LZP, Malešević NM, Savić AM, Keller T, Popović DB. Surface-distributed low-frequency asynchronous stimulation delays fatigue of stimulated muscles. Muscle Nerve 2013;48:930–937.
27. Wise AK, Morgan DL, Gregory JE, Proske U. Fatigue in mammalian skeletal muscle stimulated under computer control. J Appl Physiol 2001;90:189–197.
28. Malešević NM, Popović LZ, Schwirtlich L, Popović DB. Distributed low-frequency functional electrical stimulation delays muscle fatigue compared to conventional stimulation. Muscle Nerve 2010;42:556–562.
29. Brown TIH, Huang Y, Morgan DL, Proske U, Wise A. A new strategy for controlling the level of activation in artificially stimulated muscle. IEEE Trans Rehabil Eng 1999;7:167–173.
30. Yoshida K, Horch K. Reduced fatigue in electrically stimulated muscle using dual channel intrafascicular electrodes with interleaved stimulation. Ann Biomed Eng 1993;21:709–714.
31. Mushahwar VK, Horch KW. Proposed specifications for a lumbar spinal cord electrode array for control of lower extremities in paraplegia. IEEE Trans Rehabil Eng 1997;5:237–243.
32. Thomsen M, Veltink PH. Influence of synchronous and sequential stimulation on muscle fatigue. Med Biol Eng Comput 1997;35:186–192.
33. Nguyen R, Masani K, Micera S, Morari M, Popovic MR. Spatially distributed sequential stimulation reduces fatigue in paralyzed triceps surae muscles: a case study. Artif Organs 2011;35:1174–1180.
34. Popović LZ, Malešević NM. Muscle fatigue of quadriceps in paraplegics: comparison between single vs. multi-pad electrode surface stimulation. Proc IEEE Eng Med Biol Soc 2009;6785–6788.
35. Downey RJ, Ambrosini E, Ferrante S, Pedrocchi A, Dixon WE, Ferrigno G. Asynchronous stimulation with an electrode array reduces muscle fatigue during FES cycling. In: Proceedings of the International Functional Electrical Stimulation Society, Banff, Alberta, Canada, 2012. p 154–157.