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Comparison of Torque and Discomfort Produced by Sinusoidal and Rectangular Alternating Current Electrical Stimulation in the Quadriceps Muscle at Variable Burst Duty Cycles

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ABSTRACT

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Objective: The aim of this study was to investigate the effect of neuromuscular electrical stimulation burst duty cycle (BDC) and current type (sinusoidal alternating current [sAC] *vs.* rectangular alternating current [rAC]) on the electrically induced isometric torque (EIT) and discomfort. Pulsed current (PC) stimulation, which corresponds to one pulse rAC, was included in testing.

Design: A repeated-measures design was used. The left quadriceps of 22 healthy subjects (mean ± SD age, 33 ± 8 yrs) were stimulated alternately with sAC and rAC current bursts (4-kHz carrier frequency; 71 bursts per second burst frequency) to produce isometric contractions. A range of BDCs were tested for sAC (7%–50%) and rAC (2%–18%) stimulation at fixed intensities while EIT and discomfort were recorded. BDC presentation order was randomized.

Results: Overall, both current types elicited peak EIT at ~14% BDC (range, 7%–21%). Significantly more EIT was produced by rAC than by sAC stimulation ($P < 0.005$). Discomfort increased with BDC and was similar for both current types.

Conclusions: The study confirmed previous findings that conventional sAC stimulation (50% BDC) and pulsed current stimulation (rAC with 2% BDC) used in sports and rehabilitation produce similar EIT levels. However, rAC stimulation at low BDC (7%–18%) was more effective (+35% torque produced with similar discomfort) than pulsed current or conventional sAC.

Key Words: Middle-Frequency Stimulation, Low-Frequency Stimulation, Rehabilitation, Sports, Torque, Pain

Neuromuscular electrical stimulation is extensively used in rehabilitation[1] and sports[2,3] for muscle strengthening, muscle re-education, atrophy prevention, and restoration or support of function after injury or surgery. Particularly, it is used alone or combined with voluntary contractions in healthy athletes or postoperative knee-injured subjects because of greater muscular adaptations achieved compared with voluntary contractions.[3] The two types of stimulus waveforms commonly used are low-frequency rectangular pulsed current (PC) and kilohertz (medium)–frequency sinusoidal alternating current (sAC). PC stimulation is typically used in neuromuscular electrical stimulation rehabilitation applications and uses singular pulses with a repetition frequency of the pulses between 1 and 150 pulses per second and a pulse duration of 0.1–0.5 milliseconds (Fig. 1*A*). sAC was originally applied in muscle strengthening programs for athletes[4] and involves delivering bursts of many cycles with typical carrier frequencies of 4 or 2.5 kHz (Russian current) that are modulated at burst frequencies of 1–150 bursts per second (Fig. 1*B*).

To achieve muscle hypertrophy for rehabilitation[5] or sports purposes,[3] maximum muscle force should be elicited while limiting the client's discomfort.[1,2] Previous research has sought to determine whether sAC or PC stimulation is more efficacious, that is, elicits greater muscle force and less discomfort. However, the results of these studies do not present a clear consensus on which stimulation current type is best.[6–8] Certain studies report that greater maximal electrically induced isometric torques (EITs) are produced by PC than sAC,[6,7] whereas other studies suggest that similar levels of torque are elicited.[9,10] These previous comparisons have generally used a pulse or a cycle with a duration of 0.4 milliseconds for rAC and sAC, the highest stimulation intensity tolerable by the subjects with each current type, and a burst duty cycle (BDC) of 50% for sAC. Complicating these comparisons is that different BDCs have been used when comparing between PC and sAC. For example, one previous study[9] compared PC and sAC stimulation of the quadriceps using the same burst frequency (75 bursts per second) but different BDCs (3% PC; 51% sAC). The carrier frequency used was 2.5 kHz, which corresponds to a 0.4-millisecond cycle (pulse) duration for sAC and PC. The burst frequency of 75 bursts per second corresponds to a burst period of 13.3 milliseconds, which includes the "on-time" plus the "off-time" within the burst. The BDCs used were 3% and 51% of the total burst period, giving on-times of ~0.4 milliseconds and ~6.8 milliseconds for the PC and sAC patterns, respectively. Thus 0.4 milliseconds/

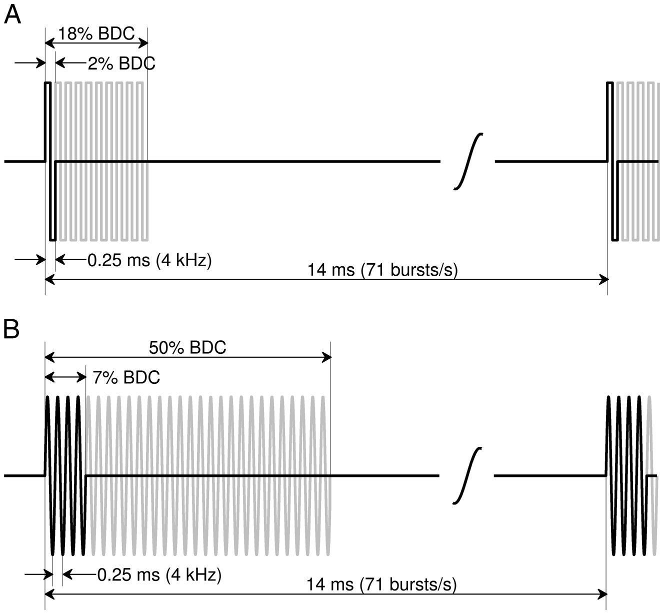

FIGURE 1 *Schematic diagram of alternating current waveforms used in this study. A, Rectangular alternating current (rAC). The waveform used had variable burst lengths between 1 and 10 cycles (2%–18% BDC, gray line). The pulsed current (PC; black line) represents a special case of rectangular alternating waveform (gray line) with one pulse. B, Sinusoidal alternating current (sAC). The waveform used had a variable burst length from 4 to 28 cycles (7%–50% BDC, e.g., 7% black line). The gray line represents conventional sAC with 50% BDC. rAC and sAC were delivered using a 4-kHz carrier frequency with a corresponding pulse and cycle duration of 0.25 milliseconds. The BDC was 71 bursts per second, giving a burst period of 14 milliseconds.*

0.4 milliseconds ~1 pulse per burst resulted for PC, and 6.8 milliseconds/0.4 milliseconds = 17 cycles per burst resulted for sAC. The authors of this study[9] found that similar forces were generated at both investigated BDCs and suggested that the additional cycles per burst (greater BDC) used in sAC stimulation did not seem to contribute to force generation.

However, findings by Laufer and Elboim[7] using the wrist muscles convincingly demonstrated that additional cycles per burst, which increase the absolute number of cycles per second, significantly increase muscle fatigue and reduce torque output. On the basis of comfort, strength, and fatigue produced by three types of sAC current and PC stimulation in the wrist muscle, these authors concluded that the PC was more advantageous over the sAC stimulation patterns. Furthermore, it was shown by Ward et al.[11] that the BDC can affect both the torque and the discomfort elicited during sAC stimulation. They investigated the torque and the discomfort produced by sAC (carrier frequencies, 2.5 and 4 kHz; burst frequency, 50 bursts per second) on the wrist extensors by varying the BDC from 0.25% to 100%. Ward et al.[11] found that the maximum torque was produced by BDCs between 10% and 20% and, more importantly, that the 50% BDC commonly used for conventional sAC stimulation did not produce maximum torque. Discomfort was also strongly dependent on BDC and was observed to be less at 20%–25% than at 50% conventional sAC stimulation.[11] In addition, Ward et al.[12] found that sAC stimulation with a 20% BDC produced the same torque levels but less discomfort as that of PC stimulation with 1% BDC.

Therefore, previous literature[7,9,11,12] is inconclusive concerning exactly how additional cycles (or pulses) per burst (greater BDC) influence the torque and the discomfort produced during stimulation. The comparison of results that tested different muscles, for example, the wrist muscle[7,11] or the quadriceps muscle,[9] may have contributed to the inconclusive findings on the relationship between BDC and torque or discomfort. Thus, whether BDC affects the quadriceps torque and discomfort should be investigated. Moreover, if there is a dependency of torque and discomfort on BDC for the quadriceps muscle, then the optimal BDC to produce maximum torque and minimum discomfort should be determined.

The goal of this study was to investigate the influence of BDC and stimulation current type on the level of torque and discomfort produced by using sAC and rectangular alternating current (rAC) stimulation of the quadriceps muscle. In this study, PC stimulation is considered as a special case of rAC with one burst pulse (Fig. 1*A*). The authors' hypothesis was that when similar cycle (pulse) durations and burst frequencies are used for sinusoidal (rectangular) waveforms, any observed differences in torque and discomfort will be dependent on the BDC within both sAC and rAC and the different waveforms used.

METHODS

Subjects and Study Design

Twenty-two healthy subjects (10 men and 12 women; mean ± SD, 33 ± 8 yrs old; weight, 78 ± 11 kg) were recruited to participate in this study. The University of Munich ethics committee approved this study, and the subjects gave their informed consent before participation. Each subject completed the experimental protocol in one session. The session consisted of EIT measurements, and the participants rated the amount of discomfort that was experienced during stimulation conditions. All sessions were completed during a 2-mo period.

Electrical Stimulation Setup

The left quadriceps muscle groups were electrically stimulated to produce isometric contractions. Pairs of self-adhesive gel electrodes (4.5×9.5 cm^2, Krauth and Timmermann, Hamburg, Germany) were used to deliver the stimulation. rAC and sAC stimulation were delivered through the same electrodes. A switch was used to select which stimulation pattern was applied. The proximal electrode was placed on the skin over the motor point at approximately one-third of the distance from the inguinal line to the superior patellar border, and the distal electrode was placed 6–8 cm proximally to the patellar border.[13]

The electrical stimulation session followed a typical strength training session[14,15] designed for torque generation. A burst frequency of 71 bursts per second was chosen for both rAC and sAC stimulation because the sAC stimulator was not technically capable of delivering 75 bursts per second.[9] The carrier frequency for sAC and rAC stimulations was set to 4 kHz, which has previously been shown to produce the least discomfort[1,11] and corresponds to a cycle and pulse duration of 0.25 milliseconds.

For rAC stimulation (Fig. 1*A*), a constant-current stimulator (Hasomed GmbH, Magdeburg, Germany) delivered rectangular, biphasic, charged balanced, or symmetric pulses. The maximum amplitude the stimulator could deliver was 127 mA. A pulse duration of 0.25 milliseconds (phase duration, 0.125 milliseconds) corresponded to a 4-kHz carrier frequency. The stimulator was purposely modified to be able to provide one to ten pulses per burst, allowing BDCs of 2%, 4%, 5%, 7%, 9%, 11%, 12.5%, 14%, 16%, and 18% to be tested (rAC with one pulse [2% BDC] corresponded to PC stimulation). For sAC stimulation (Fig. 1*B*), a middle-frequency constant-current stimulator (ETI GmbH, Karlsruhe, Germany) was used. The maximal sinusoid current delivered was 140 mA peak to peak. The burst on time could be adjusted by 1-millisecond steps (~7% BDC, equivalent to four cycles of a duration of 0.250 milliseconds), allowing BDCs of 7%, 14%, 21%, 29%, 36%, 43%, and 50% to be selected.

EIT Measurements

A stationary tricycle that had its front wheel replaced with a torque transducer (T30FN, Hottinger GmbH, Darmstadt, Germany) served as the test bed for the isometric measurements. The EIT that was produced by the left quadriceps muscle was measured at a fixed crank angle of 120 degrees; zero degree was defined as when the crank points horizontally backward. The ankle joint was fixed at 90 degrees, and sagittal-plane movement of the leg was minimized by using a shank and foot orthosis. The knee flexion angle was held constant during all torque measurements. Knee angle was measured with a goniometer (group mean ± SD, 83 ± 21 degrees). A personal computer recorded torque data at a sampling rate of 1 kHz.

Stimulation Amplitude

The stimulation amplitudes used for the testing protocols were the maximum that the subjects thought they could tolerate for 20 mins. The procedure to determine the maximum stimulation amplitude began with the researcher increasing the stimulation intensity from 0 mA by a rate of ~2 mA per sec. The subjects were instructed to indicate when the stimulation reached the greatest stimulation intensity that they thought they could tolerate for 20 mins. At this instant, stimulation was held constant for 2.5 secs. If the subject tolerated the stimulation intensity for 2.5 secs and still believed that he/she could tolerate it for 20 mins, then the stimulation amplitude was recorded. This procedure was repeated until three consistent amplitudes were observed (i.e., range of variations <10%). A BDC as close to 20% as technically possible (i.e., 18% for rAC and 21% for sAC) was used because, on the basis of previous literature, a BDC of 20% was thought to be near optimal for evoking maximum EIT.[11,16] Separate maximum stimulation amplitudes were determined for sAC and rAC. The abovementioned procedure was repeated at the very end of the testing session. These maximum stimulation amplitudes were used in all subsequent comparison measurements of sAC and rAC stimulation, including all possible BDCs. Because the maximum stimulation amplitude was determined at ~20% BDC, this amplitude was expected[11] to produce more discomfort at other BDCs. Therefore, the subjects were informed that intermittently during the session, the discomfort produced by the stimulation would be "somewhat higher" (based on preliminary measurements <20% on the numerical rating scale [NRS], see below) than experienced at 20% BDC. The subjects were also informed that they were allowed to interrupt or abort the experiment at any time. The maximum stimulation amplitudes were fixed and used for the remainder of the session.

Comparison Measurements of sAC vs. rAC

The sAC *vs.* rAC protocol consecutively measures the EIT and the discomfort produced by rAC and sAC stimulation to minimize the effect of testing order on the results. For this purpose, the type of stimulation current was alternated between consecutive stimulations by rapidly switching between stimulators with an electronic switch. The beginning pattern (i.e., rAC or sAC) was chosen randomly. The protocol (Fig. 2*A*) included four BDC conditions for sAC (7%, 14%, 21%, and 50%) and four for rAC (2%, 7%, 14%, and 18%). Eight stimulation blocks were administered, and each block contained eight stimulation periods that corresponded to the eight BDC conditions (four sAC + four rAC). Within each block, the eight BDC conditions were presented in a different randomly permutated order (two random samples are shown in Fig. 2*A*). Thus, a total of 8 stimulations × 8 blocks (= 64 stimulation periods) were presented in a quasi-simultaneous randomized order. The presentation order was also balanced such that an equal number (eight) of measurements were collected for each stimulation condition. Because each stimulation period lasted 20 secs (with an interruption modulation of 5 secs on-time/15 secs off-time[9]) for both current types, the sAC *vs.* rAC protocol lasted a total of 1280 secs (64 stimulations × 20 secs). The EIT produced during the on-time was recorded. The subjects were instructed to verbally estimate for every stimulation condition their pain or discomfort from 0 to 10 on the NRS[17]; a rating of 0 corresponded to "no pain or uncomfortable sensations" and a rating of 10 corresponded to "worst pain imaginable." The subjects reported the discomfort immediately after the administration of each contraction, that is, during the 15-sec off-time.

Extended Torque Measurements

In a subset of five subjects, two additional torque measurement sequences were performed to obtain more information on the relationship between EIT

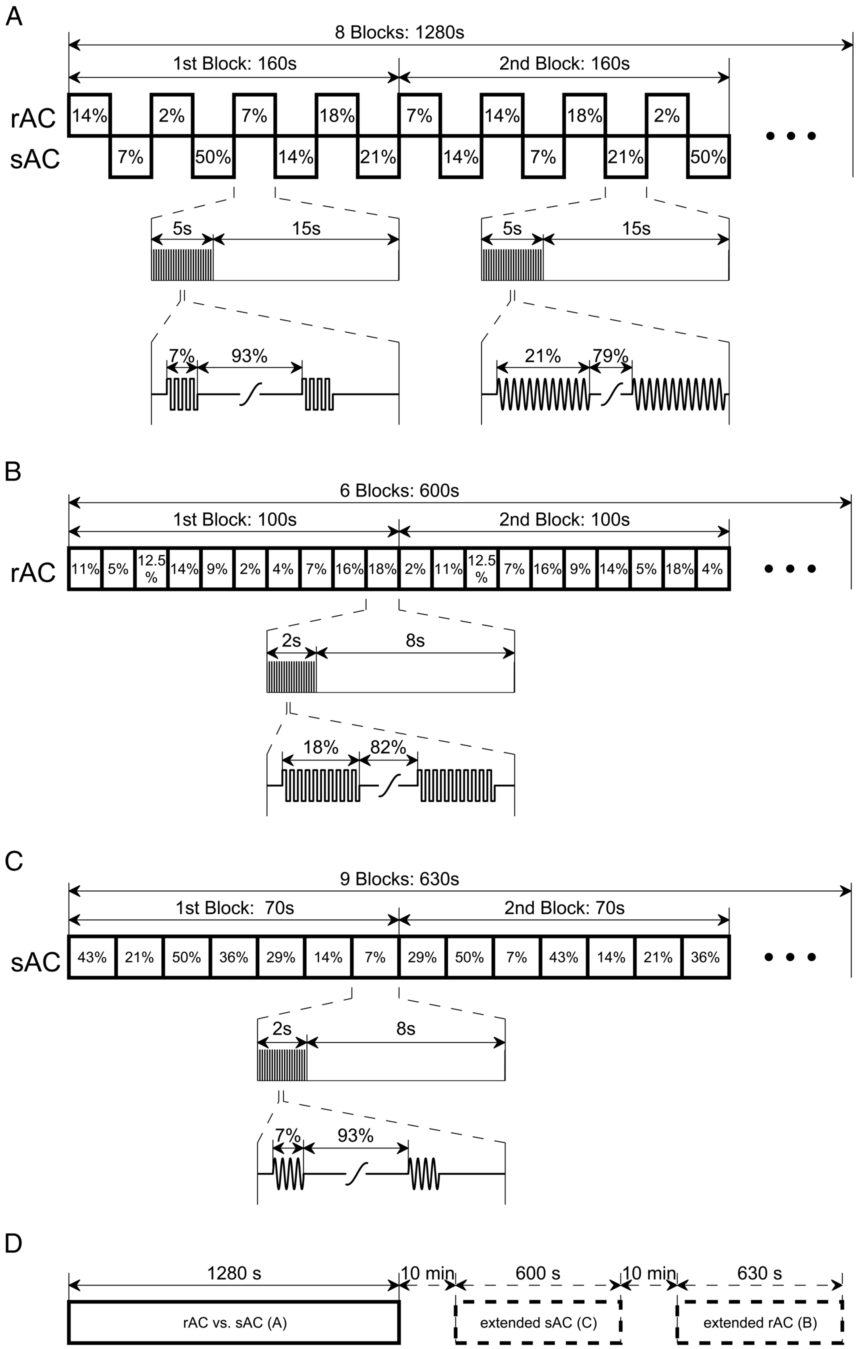

FIGURE 2 *Measurement protocols used. A, Sinusoidal vs. rectangular alternating current comparison protocol (sAC vs. rAC). The rAC and sAC stimulations were alternately performed by switching the stimulators between two consecutive stimulations. Four BDC conditions for rAC (2%, 7%, 14%, and 18%) and four for sAC stimulation (7%, 14%, 21%, and 50%) were used. Eight stimulation blocks were administered, and each block contained eight stimulation periods that corresponded to the eight BDC conditions (four rectangular + four sinusoidal). Within each block, the eight BDC conditions were presented in a different randomly permutated order (two random samples are shown). The stimulation period was 20 secs, with interruption modulation of 5 secs on/15 secs off. The conditions rAC at 7% and sAC at 21% BDC are shown as an example. B, The extended rectangular alternating current protocol (extended rAC). Ten BDC conditions (2%, 4%, 5%, 7%, 9%, 11%, 12.5%, 14%, 16%, and 18%) were used. Six stimulation blocks of rAC stimulation were delivered, and each block contained ten stimulations periods. The BDCs were presented in a different randomly permutated order (two random samples are shown). The stimulation period was 10 secs (2 secs on/8 secs off). C, The extended sinusoidal alternating current protocol (extended sAC). Seven BDCs were presented (7%, 14%, 21%, 29%, 36%, 43%, and 50%), with nine random permutations. Nine blocks of sAC stimulation each containing the seven randomly permutated BDCs were delivered (two random samples are shown). The stimulation period was 10 secs (2 secs on/8 secs off). D, Timeline diagram the measurement protocols. All subjects underwent the sAC vs. rAC protocol, and five subjects also performed both the extended sAC and the extended rAC protocols in the fixed order illustrated.*

and BDC. Each sequence involved only one stimulation current type (e.g., rAC or sAC), but more BDCs were tested (Fig. 2*D*).

The extended rAC protocol (Fig. 2*B*) recorded the torques that were evoked with the ten different BDCs that could be produced with rAC stimulation (i.e., 2%, 4%, 5%, 7%, 9%, 11%, 12.5%, 14%, 16%, and 18%). Six stimulation blocks were delivered, and each block consisted of ten stimulations periods. Each period (i.e., 2 secs on followed by 8 secs off) within a block used a different BDC. The BDCs were presented in a randomly permutated order. The authors expected the torque values recorded with the extended protocol to be reduced by fatigue because of previous exposure to the sAC *vs.* rAC protocol. Therefore, a shorter stimulation period of 10 secs (interruption modulation of 2 secs on-time/8 secs off-time) was used during extended testing to reduce further fatigue and allow stimulation trials to be completed. The extended rAC protocol (Fig. 2*B*) lasted 600 secs (6 blocks × 10 stimulations × 10 secs). The extended sAC protocol (Fig. 2*C*) collected torque data from seven different BDCs (i.e., 7%, 14%, 21%, 29%, 36%, 43%, and 50%). Nine blocks of stimulation that each contained seven randomly permutated BDCs were delivered. The stimulation period was also 10 secs (2 secs on/8 secs off), making the total duration of the extended sAC protocol 630 secs (7 stimulations × 9 blocks × 10 secs).

Data Processing

To obtain the test-retest reliability[18] for the maximum stimulation amplitudes for rAC and sAC, the intraclass correlation coefficients (ICCs) were calculated for all subjects ($N = 22$) using the mean values of the three measurements for rAC and sAC from the beginning and the end of each session (ICC [1-k][19]). The reliability[18] of the torque and pain data was obtained by computing the ICC (1-1)[19] on the basis of the eight measurements collected for each BCD during the sAC *vs.* rAC protocol.

The mean torque for each contraction was calculated from the mean area under the EIT curve during the central 80% of the stimulation on-time. The data were then analyzed to examine the dependencies of torque and discomfort on the BDC and the current type. For each protocol and each subject, the torques obtained were normalized against the torque produced (in that subject) with the BDC that produced the greatest torque for most subjects. The purpose of the normalization was to eliminate the effects of intrasubject variability on torque, which could potentially confound within-group comparisons. The discomfort data for each subject were normalized to the maximum measurement recorded for that subject.

Because a normal distribution could not be assumed for the normalized data collected with the rAC *vs.* sAC protocol ($n = 22$), distribution-independent, two-factor permutation analyses of variance[20] with 2000 permutations were used to investigate the effect of BDC and current type on the torque and the discomfort. Corrections for post hoc multiple comparisons were based on the robust false-detection rate procedure.[21] Results were represented as mean ± standard deviation, and comparisons were considered to be significant at $P < 0.05$. The analyses were performed using the Statistics Toolbox in Matlab 7.12.0 (The MathWorks Inc, Natick, United States).

RESULTS

Maximum Stimulation Amplitudes

The maximum tolerated stimulation amplitudes determined at the beginning of the sessions were 70 ± 7 mA (rAC, 18% BDC) and 45 ± 9 mA (sAC, 21% BDC). After the completion of the measurement sessions, the amplitudes were found to be 75 ± 16 mA (rAC) and 48 ± 14 mA (sAC), indicating a nonsignificant increase in the pain tolerance for both rAC ($P = 0.14$) and sAC stimulation ($P = 0.41$). The test-retest reliabilities of the maximum stimulation amplitudes were excellent and fair to good for rAC and sAC (ICCs = 0.78 and 0.73, respectively [Table 1]).

Extraction of the Torque vs. BDC Relationships

For each subject, the EIT data recorded during the sAC *vs.* rAC protocol were separated into rAC- and sAC-induced contractions to obtain two torque sequences. These torque sequences each contained 32 measurements (4 BDC conditions × 8 replications). Excellent reliabilities were found for the measurements taken over the eight replications for each BDC for rAC (ICC range, 0.83–0.91, for the four BDCs [Table 1]); and fair to good reliabilities, for sAC (ICC range, 0.50–0.60). The torque sequences (for a representative subject in Figs. 3*A*, *B*) show variable magnitudes caused by the dependency on the four BDC conditions. In addition, there was pronounced torque decay with time, which is likely caused by stimulation-induced fatigue (Figs. 3*A*, *B*). The torque *vs.* BDC scatter plots are shown in Figures 3*C* and *D*. The effect of fatigue resulted in large scattering of data at each BDC and obscured the effect of the BDC on the EIT.

Therefore, it was necessary to minimize the bias of fatigue by modeling and then correcting the data

TABLE 1 Reliability of maximum stimulation amplitude, EIT, and discomfort measurements

		BDC				
		2%	7%	14%	18%/21%	50%
Maximum stimulation amplitude	rAC	—	—	—	0.78 (0.48–0.91)	—
	sAC	—	—	—	0.73 (0.35–0.89)	—
EIT Uncompensated	rAC	0.91 (0.86–0.96)	0.84 (0.74–0.92)	0.83 (0.73–0.91)	0.84 (0.74–0.92)	—
Compensated		0.98 (0.96–0.99)	0.95 (0.92–0.98)	0.96 (0.93–0.98)	0.97 (0.94–0.98)	—
Uncompensated	sAC	—	0.50 (0.34–0.69)	0.54 (0.38–0.73)	0.51 (0.35–0.70)	0.60 (0.43–0.78)
Compensated		—	0.96 (0.93–0.99)	0.97 (0.95–0.99)	0.97 (0.94–0.99)	0.98 (0.96–0.99)
Discomfort NRS	rAC	0.90 (0.71–0.99)	0.77 (0.46–0.98)	0.89 (0.68–0.99)	0.89 (0.67–0.99)	—
	sAC	—	0.64 (0.29–0.96)	0.73 (0.41–0.98)	0.87 (0.65–0.99)	0.91 (0.74–0.99)

Values are expressed as ICC (95% confidence interval). ICC of 0.4 or less indicates poor reliability, ICC of greater than 0.4 and less than 0.75 indicates fair to good reliability; and ICC of 0.75 or greater indicates excellent reliability.[18]

NRS indicates NRS of discomfort.

for their effect on the rAC and sAC torque measurements.[11] For this purpose, the authors modeled the decay of the mean torque data corresponding to the 18% BDC (rAC) and the 50% BDC (sAC) stimulation as interpolation points to construct two 10th-degree polynomials that represented torque decay for rAC and sAC (Figs. 3*A*, *B*). Subsequently, all of the torque samples except for the initial values were scaled on the basis of the modeled torque decay curves to compensate for fatigue. This magnified all of the other torque values by a corresponding scale as though no fatigue had occurred. This compensation reduced

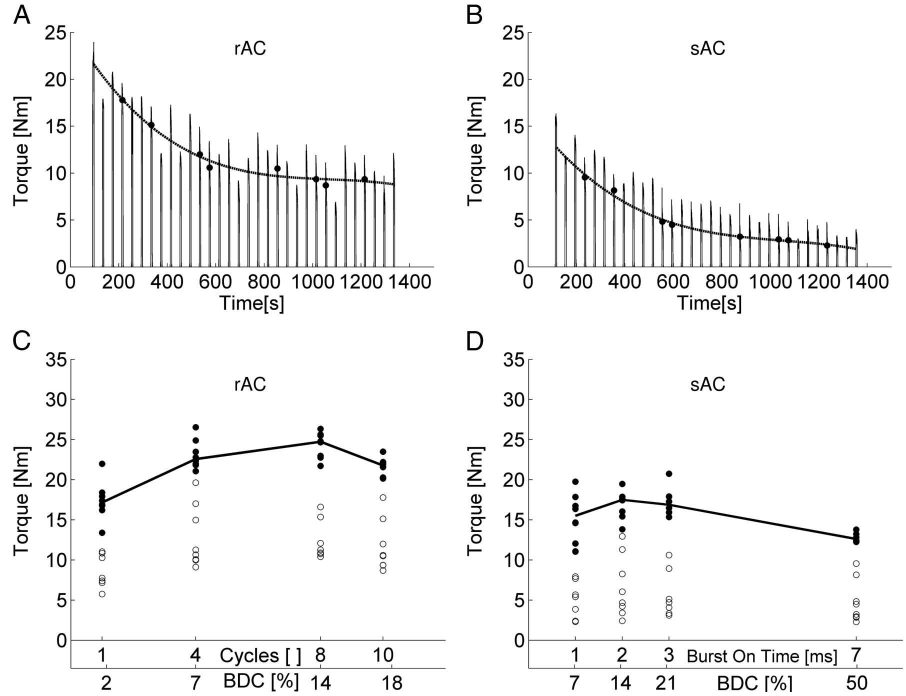

FIGURE 3 *Torque data obtained from a representative subject with the sAC vs. rAC protocol. A, Separate time course of the torques evoked by rAC contractions. B, Separate time course of the torques evoked by sAC contractions. Both sequences contained 32 torque spikes that showed variable magnitudes, corresponding to the four BDC conditions presented. Pronounced fatigue effects causing torque decays were also present. For rAC, the torque decay representing fatigue was modeled by a tenth-degree polynomial (dotted line) using the eight torque values obtained with 18% BCD as interpolation points (•). For sAC, the torque decay was interpolated (dotted line) using the eight torque values corresponding to 50% BCD (•). C, Torque vs. BDC scatter plot for rAC current type. D, Torque vs. BDC scatter plot for sAC current type. The scatter plots were obtained from the time sequences by sorting the mean torques according to the four BDC conditions. Because of fatigue effects, the uncompensated torques (○) show large scattering, blurring the effect of the BDC on the torque. However, scaling the uncompensated torques to account for fatigue decay produced compensated torques (•) that clearly show the torque vs. BDC relationships. The mean values of the compensated torques are connected by lines.*

the effect of fatigue on the data. The reliability of both the rAC and sAC torque data was excellent after compensation (ICC ranges, 0.95–0.98 and 0.96–0.98, respectively [Table 1]). The mean values of the compensated torques provided the torque *vs.* BDC relationships for the subjects (Figs. 3*C*, *D*).

The data from the five subjects who performed the extended trials were treated in a similar manner; mean torques were extracted from the extended rAC and the extended sAC trials, then scaled on the basis of the modeling of their respective extracted decay curves (18% BDC for rAC, 50% BDC for sAC). The mean values of the scaled torques were used to construct torque *vs.* BDC relationships for each of the five subjects.

The Influence of BDC on Torque

The data from the sAC *vs.* rAC protocol demonstrated that rAC current with 14% BDC produced the maximum torque for both stimulation current types in most of the 22 subjects. Therefore, the torques that were obtained for each subject with this protocol were normalized to the rAC torque generated at the 14% BDC for that subject (Fig. 4*A*). For the extended protocols, it was found that maximum torque was produced always at the BDCs

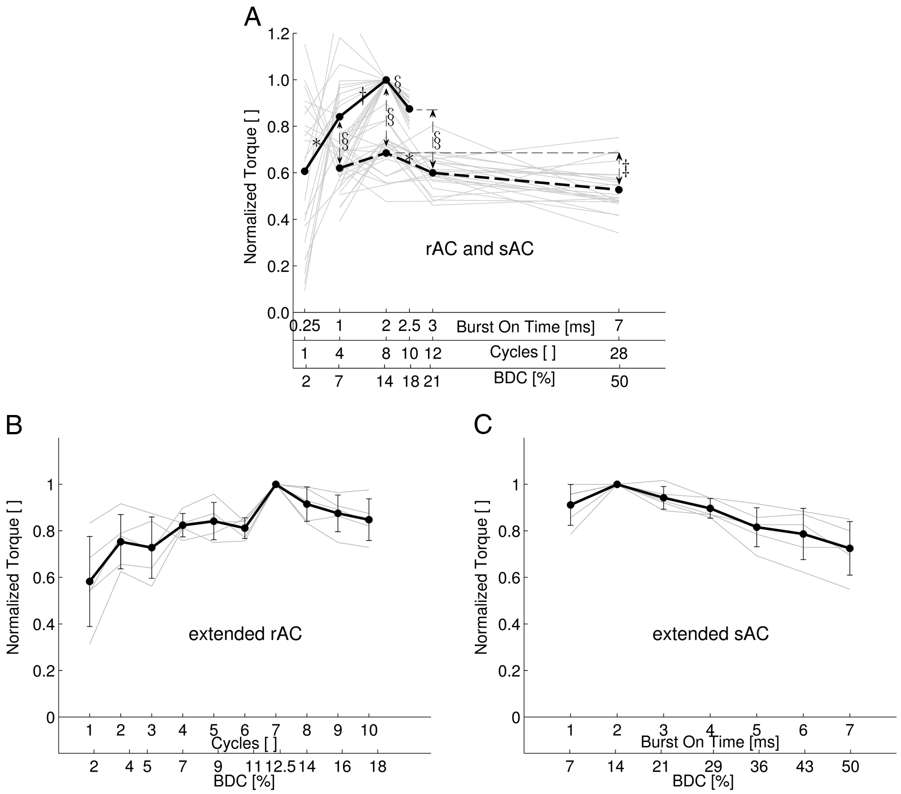

FIGURE 4 *Mean normalized torque vs. BDC. A, Normalized rAC and sAC torques extracted with the sAC vs. rAC protocol (computed as EIT/EIT [rAC14]). The normalization was performed for each subject against the torque obtained in the same subject with rAC using a BDC of 14% (EIT [rAC14]), which produced maximum torque for most subjects. Normalized torque vs. duty cycle graphs are presented for each subject (thin lines). The group means (•, N = 22) of the normalized torques for rAC and sAC are connected by continuous bold and dashed bold lines, respectively. Post hoc comparison of normalized torque levels resulted in the significances that are plotted on the graph or near the vertical double arrows in the figure. *P < 0.05; †P < 0.01; ‡P < 0.005; §P < 0.001. B, Normalized rAC torques extracted with the extended rAC protocol (computed as EIT/EIT [rAC12.5]). The normalization was performed for each subject against the torque obtained in the same subject with rAC using a BDC of 12.5% (EIT [rAC12.5]), which produced maximum torque for all subjects who underwent the extended rAC protocol. Normalized torques were drawn for each subject using thin gray lines. Group means (•, n = 5) of the normalized torques are connected by continuous bold black lines, and standard deviations are represented by vertical thin lines. C, Normalized sAC torques extracted with the extended sAC protocol (computed as EIT/EIT [sAC14]). The normalization was performed for each subject against the torque of the same subject obtained with sAC at a BDC of 14% (EIT [sAC14]), which produced maximum torque for most subjects who underwent the extended sAC protocol. Normalized torques were drawn for each subject using thin gray lines. Group means (•, n = 5) of the normalized torques are connected by continuous bold black lines, and standard deviations are represented by vertical thin lines.*

of 12.5% and 14% for rAC and sAC stimulation, respectively. Correspondingly, the authors normalized the torques collected with the extended protocols to the torques produced at a BDC of 12.5% or 14% (Figs. 4*B*, *C*).

The permutation two-factor analysis of variance with the independent variables BDC (five levels) and current types (two levels: rAC and sAC) for the normalized torque data collected with the sAC *vs.* rAC protocol revealed significant dependencies on BDC ($P < 0.001$) and current type ($P < 0.001$). There was no significant interaction effect of BDC and current type on the EIT levels of quadriceps torque ($P = 0.15$). The mean normalized torque *vs.* BDC curve for rAC exhibited a pronounced peak at the 14% BDC (Fig. 4*A*). The normalized torque was significantly lower at 2% ($P < 0.01$), 7% ($P < 0.01$), and 18% BDCs ($P < 0.001$) than at the maximum. The mean normalized torque curve for sAC indicates that maximum torque production also occurred at the 14% BDC (Fig. 4*A*). However, this curve displayed a less pronounced peak at 14% BDC, with a flatter decay to the left (nonsignificant difference with respect to 7% BDC) and a more pronounced decay to the right ($P < 0.05$ difference with respect to 21% BDC). Moreover, the normalized torque further decayed and reached a minimum at a 50% BDC. The maximum torque that was observed at 14% BDC was significantly higher than the minimum ($P = 0.005$).

The Influence of Current Type on Torque

Torque was significantly dependent on stimulation current type (Fig. 4*A*) when comparing rAC with sAC stimulation in the range of 7% to 18%–21% BDC. Significantly more torque was produced by rAC than by sAC stimulation in this range ($P = 0.001$ at 7%, $P < 0.001$ at 14% and $P < 0.001$ between 18% and 21% BDC); in particular, the peak of the normalized torque at 14% BDC for rAC exceeded the peak for sAC by 35%. Moreover, the normalized torque for rAC stimulation with one pulse and 2% BDC (PC stimulation) did not differ significantly ($P > 0.9$) from the normalized torque obtained with sAC at any measured BDC, including the 50% BDC (conventional sAC stimulation) and the peak torque at 14% BDC.

The Influence of BDC on Discomfort

The NRS discomfort recorded in each subject (eight replications for each BDC) showed excellent reliabilities for rAC (ICC range, 0.77–0.90 [Table 1]) and fair to good and excellent reliabilities for sAC (ICC range, 0.64–0.91). The mean NRS-rated discomfort experienced during rAC or sAC stimulation was computed in each subject by taking the mean of the eight measurement points from each BDC (Figs. 5*A*, *B*). The highest discomfort rating was recorded during sAC stimulation at 50% BDC in all subjects. The authors therefore normalized the NRS *vs.* BDC curves using the discomfort rating at 50% BDC sAC for each subject (Fig. 5*C*).

The permutation two-factor analysis of variance with the independent variables BDC (five levels) and current type (two levels: rAC and sAC) for the normalized discomfort data revealed a significant dependence on BDC ($P < 0.001$), with no significant dependence on stimulation current type ($P = 0.53$) and a significant interaction between factors ($P = 0.02$). The post hoc multiple comparisons of the eight conditions resulted in five groups (Fig. 5*C*) with similar discomfort levels, whereas the between groups did significantly differ: (1) rAC at 2%, (2) sAC and rAC at 7%, (3) sAC at 14%, (4) rAC at 14% and 18% and sAC at 21%, and (5) sAC at 50% BDC. For both current types, the discomfort increased with the BDC for the range investigated. The discomfort levels with rAC at 18% and sAC at 21% did not differ significantly; this was expected given that the maximum stimulation intensities for sAC and rAC stimulation were defined at these BDCs. As predicted, the discomfort that was produced with sAC at 50% BDC significantly exceeded ($P < 0.001$) the discomfort that occurred at the rAC at 18% or sAC at 21% BDC by approximately 0.2 normalized NRS units.

The Torque Discomfort Relationship

The efficacy of stimulation is represented by the relationship between torque and NRS discomfort.[22] To investigate the efficacy of stimulation, the normalized torque and NRS plots against BDC were combined into normalized torque *vs.* normalized NRS plots (Fig. 6). For example, for rAC, the normalized torque *vs.* BDC curve (Fig. 4*A* continuous line) was combined with the normalized NRS discomfort for rAC *vs.* BDC curve (Fig. 5*C* continuous line), obtaining the normalized torque *vs.* normalized discomfort curve in Figure 6 (continuous line), whereas the BDC served as a parameter. This representation allows for easy efficacy comparisons based on fixed torque or discomfort. For example, the torque generated by sAC stimulation changed only slightly, when the discomfort varied in the 0.7–1 range. Furthermore, PC stimulation (rAC with one pulse = 2% BDC) produced torque that was very similar to that produced by sAC stimulation for all the tested BDCs but with less discomfort.

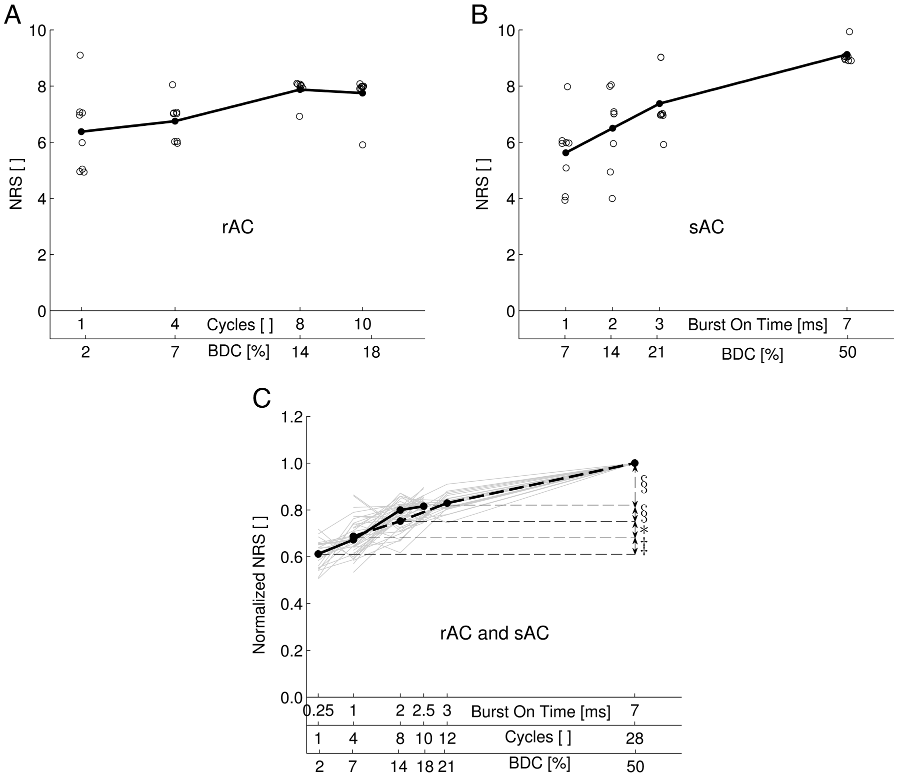

FIGURE 5 *Discomfort vs. BDC graphs obtained with the sAC vs. rAC protocol. A, For rAC, the stimulation experienced discomfort expressed as NRS obtained in the representative subject. According to the NRS, a rating of 0 corresponded to "no pain or uncomfortable sensations" and a rating of 10 corresponded to "worst pain imaginable." The mean values (•; connected by lines) were taken over the eight replication measurements (○) for each BDC presented during the protocol (B). For sAC, the stimulation experienced discomfort expressed as NRS obtained in the representative subject. The mean values (•; connected by lines) were taken over the eight replication measurements (○) for each BDC presented during the protocol. The position of the open circles was slightly altered in (A) and (B) to avoid overlap. C, For rAC and sAC, the stimulation experienced discomfort represented as normalized NRS (computed as NRS/NRS [sAC50]). The normalization was performed for each subject against the NRS obtained in the subject with sAC at BDC 50% (NRS [sAC50]). All subjects reported the highest NRS with this condition. Normalized NRS vs. BDC graphs are presented for each subject (thin gray lines). The group means (•, N = 22) of the normalized NRS for rAC and sAC are connected by continuous bold and dashed bold lines, respectively. Post hoc comparison of normalized discomfort levels resulted in significant differences between the stimulation conditions: rAC at 2%; sAC at 7% and rAC at 7% together; sAC at 14%; rAC at 14%, rAC at 18%, and sAC at 21% together; and sAC at 50% BDC. The significances are plotted near the vertical double arrows. *$P < 0.05$; †$P < 0.01$; ‡$P < 0.005$; §$P < 0.001$.*

Unlike the torque produced by sAC stimulation, the torque generated by rAC stimulation varied strongly in the 0.6–0.8 discomfort range. Therefore, torque seems to be markedly dependent on stimulation current type; indeed, 35%–54% more torque will be produced using rAC than sAC stimulation in the 0.7–0.85 discomfort range.

DISCUSSION

The present study investigated the dependence of torque and discomfort on the BDC and the current type of stimulation (rAC *vs.* sAC) in the quadriceps. The primary findings were that torque was significantly dependent on BDC and current type. Discomfort was significantly dependent on the BDC. In particular, (1) the maximum torque was produced at a BDC of 14%, irrespective of the stimulation current type; (2) the discomfort increased with greater BDC; and (3) significantly more torque could be produced by rAC than by sAC stimulation if an intermediate BDC range (7% to 18%–21%) was used or if both current types were considered at the same normalized discomfort level of ~0.7–0.8.

The Dependence of Torque on BDC

The authors observed that the torque produced increased as BDC was increased in its low range (Fig. 4*A*). This observation can be explained by previous literature and knowledge. Suprathreshold intensities of alternating current stimulation with long

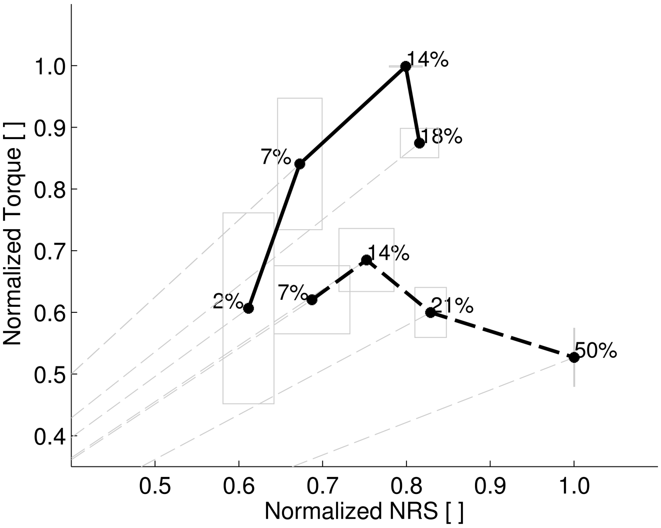

FIGURE 6 *Mean normalized torque vs. mean normalized discomfort relationships (normalized torque given by EIT/EIT [rAC14]; normalized discomfort given by NRS/NRS [sAC50]). The curves were obtained by combining normalized torque vs. BDC relationships from Figure 4A with the normalized discomfort vs. BDC relationships from for each subject against the EIT at rAC with 14% BDC (EIT [rAC14%]). NRS normalization was performed for each subject against the NRS at sAC with 50% BDC (NRS [sAC50%]). The group means (•, N = 22) for rAC and sAC are connected by continuous bold and dashed black lines, respectively. The standard deviations of normalized torque and normalized NRS are marked by thin-lined rectangles. For each stimulation condition, a dotted line was drawn connecting the corresponding group mean (•) to the origin of the coordinate axes. The slopes of these lines correspond to the stimulation efficacy (torque/discomfort ratio) of the corresponding condition.*

duration bursts can activate multiple nerve fiber action potentials per burst, producing firing rates that are multiples of the burst frequency.[23,24] Nerve fiber firing of hundreds of hertz can be elicited with an upper limit of approximately 1 kHz, which is dictated by the absolute refractory period of the nerve.[25] Correspondingly, if more than one cycle per burst is used such as in the present study, action potentials can be elicited at multiples of the burst frequency, causing the muscle fiber twitches to result in greater muscle torque being elicited because of muscle fiber twitch summation.

Nevertheless, if the burst length is too long, fewer action potentials will be evoked because of neurotransmitter depletion, propagation failure,[26] or even nerve conduction block.[25] The fiber dropout occurring during alternating current stimulation is caused by high-frequency fatigue as a result of propagation failure.[7] Laufer and Elboim[7] elucidated that the fatigue resulting from burst-modulated currents depended not on the burst frequency but on the number of cycles per second delivered to the tissue. Moreover, in a recent study on the quadriceps muscle, Parker et al.[27] showed that current patterns with higher BDCs (greater number of cycles per second) produced fewer muscle contractions than those with lower BDC (lower number of cycles per second). The reduced force produced during the high BDC pattern was also assumed to be caused by fatigue induced by the delivery of a greater number of cycles per second to the muscle. This could explain the trend of decreasing torque that was observed at higher BDCs because the greater BDC of 50% *vs.* 14% resulted in greater cycles and pulses per second to the tissue (1988 and 568 cycles per second, respectively), at 4-kHz carrier and 71-Hz burst frequency.

The present study showed that both rAC and sAC stimulation generated a pronounced and a flat peak torque, respectively, at 14% BDC (Fig. 4*A*). Considering the extended rAC measurements, the peak of the rAC-stimulation–evoked torque appears at a somewhat lower BDC, at 12.5% (Fig. 4*B*). The greater and more pronounced peak in generated torque with rAC stimulation may be because the stimulation waveform more effectively creates cumulative summation[28] of subthreshold depolarization of the nerve fiber membranes (Fig. 4A) compared with sAC.

These findings correspond with and generalize previous results in the hand/wrist extensors that revealed that maximum torque production via sAC stimulation occurs in the 10%–20% BDC range.[11] These authors also assumed that, if a 4-KHz carrier frequency was used, the optimal BDC would be 12.5%. Other studies using sAC stimulation have also predicted maximum torque to be achieved at the 20%[29] and 12% duty cycles.[30] Furthermore, the approximately linear decline of the sAC torque in the higher BDC (14%–50%) range (Figs. 4*A*, *C*) is also consistent with earlier observations in the wrist extensor muscles.[11]

Dependence of Discomfort on BDC

In the current study, subjective pain or discomfort was quantified and expressed verbally according to the NRS.[31] Previous studies used either the NRS or a visual analog scale to record discomfort at fixed isometric torque levels.[22,32] Alternatively, the stimulation current intensity or voltage[16] required to reach sensory or pain thresholds was measured. In other research, the number of discomfort reports was simply counted.[11] Using the NRS, the authors of the present study relied directly on subjectively sensed discomfort rather than assuming that the discomfort was proportional to the stimulation current (density)[33] or voltage.[11]

The discomfort increased with BDC (Fig. 5*C*), reaching its maximum at the highest considered magnitude at 18% and 50% BDC for rAC and sAC, respectively. In contrast to others,[11] who used the number of discomfort reports as a measure of the discomfort level experienced, the NRS discomfort ratings in this study did not increase at low (<10%) BDC. Using lower BDCs in the kilohertz carrier frequency range for stimulation is more comfortable than using high BDCs, possibly because gating of pain fiber activity is most efficient at less than ~200-Hz stimulation of the sensory fibers[1] (corresponding to a BDC of lower than ~5% at 4-kHz carrier frequency).

The Efficacy of Stimulation Modes

The torque *vs.* discomfort curve was used to define sAC and rAC stimulation efficacy[22] by comparing torque at similar discomfort (or comparing discomfort at similar torque). The torque that was generated using sAC was weakly dependent on the level of discomfort, whereas with rAC stimulation, there was a strong dependency on discomfort with a pronounced maximum (Fig. 6). Similar torques were produced with rAC at 2% and sAC at 7%, 21%, and 50% BDC, with increasing discomfort levels. Although the results of this study strongly support previous findings[11] demonstrating that torque generated with PC stimulation (corresponding to rAC with one pulse) is similar to that produced by conventional sAC (50% BDC) at 2.5-KHz carrier frequency and 75 bursts per second burst frequency, it was additionally concluded that the amount of discomfort caused by these stimulation conditions was different. Specifically, the sAC with 50% BDC was more uncomfortable than the PC stimulation (rAC with one pulse or 2% BDC). This result supports the previous finding[34] that PC stimulation of the quadriceps was perceived as more comfortable than conventional sAC (50% BDC) at 50 Hz.

Furthermore, the authors found that rAC stimulation (at 7%, 14%, and 18% BDC) produced as much as 35% more torque than did sAC stimulation (at 7%, 14%, and 21% BDC) at the same discomfort level in the normalized NRS range of 0.7–0.82 (Fig. 6). To the authors' best knowledge, there are few data or models published that compare torques produced by rAC *vs.* sAC at similar BDC or discomfort levels, except for those at one pulse[35] or 50% BDC.[34] Simulations-based studies on one pulse/cycle wave stimulation have reported a lower chronaxie time (higher excitability)[36] or higher power efficiency[37] for rectangular waves compared with sine waves, which could result in less discomfort produced by rectangular than sinusoidal stimulation. Further studies are needed on the effect of waveform type on torque and efficiency in the BDC range between 7% and 20% to understand the electrophysiology underpinning these observations.

The present study analyzed the efficacy of a given stimulation condition by the relationship between torque and discomfort. Efficacy could be alternatively defined as the torque/discomfort ratio (represented by the slopes of the lines passing through the origin for that condition (Fig. 6). This definition is similar to that given by the torque/stimulation voltage ratio,[11] given that the level of experienced discomfort based on the NRS scale may be assumed to be proportional to the stimulation intensity.[22] Considering rAC stimulation, Figure 6 shows that the slope that corresponds to the torque values obtained with 7%–14% BDC is at a maximum compared with the slopes at 2% and 18% BDC, indicating that the highest efficacy of rAC stimulation is achieved when using a 7%–14% BDC. The same range is suggested to be optimally efficient for sAC stimulation on the basis of the analysis of the torque *vs.* discomfort slopes, confirming similar results[11] for the wrist-extensor muscles (~12% BDC).

CONCLUSIONS

The present study comparing sAC and rAC stimulation with 4-kHz carrier and 71 bursts per second burst frequency demonstrated the dependency of the EIT on BDC and current type. Discomfort depended on the BDC. This study confirmed that conventional sAC stimulation (50% BDC [the clinically common Russian-type stimulation]) is equivalent to PC stimulation in terms of EIT. In contrast to PC and conventional sAC stimulation, as much as 35% more torque could be evoked by rAC than by sAC stimulation at a similar level of discomfort using optimal BDC in the 7%–20% range. The results are relevant for practitioners, who could plan more efficient electrical stimulation to achieve muscle hypertrophy for sports purposes or rehabilitation of individuals with preserved sensation.

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