ON / OFF TIME (DUTY CYCLE) FOR MUSCLE STRENGTHENING

Electrical Stimulation Parameters in Pediatric Neuromuscular Rehabilitation — tSCS / NMES

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1. Purpose

This document consolidates current literature on stimulation on-time and off-time (duty cycle) for neuromuscular electrical stimulation (NMES) and transcutaneous spinal cord stimulation (tSCS), with a specific focus on muscle strengthening applications in children. The aim is to build clarity around how on/off timing should be set and progressed in order to balance effective muscle activation against fatigue, so that strengthening protocols are optimized and safe for the pediatric neuromuscular population.

> *This is a working research synthesis for internal clinical use and protocol development. It is not a substitute for individualized clinical judgment, and all parameters should continue to be adjusted per patient as already practiced.*

2. Why Off-Time Matters: The Underlying Principle

Electrically-evoked contractions differ fundamentally from voluntary contractions. NMES recruits motor units synchronously and in a fixed spatial pattern beneath the electrodes, rather than the asynchronous, rotating recruitment seen in voluntary effort. This non-physiological recruitment pattern — combined with a bias toward superficial, fast-twitch fibers — causes electrically-evoked contractions to fatigue considerably faster than voluntary ones.

The off-time (rest interval) exists to let the muscle recover between contractions before the next one is triggered. If the off-time is too short relative to the on-time, recovery is incomplete, evoked force drops across the session, and the therapeutic stimulus becomes progressively weaker and more uncomfortable. If the off-time is too long, total session time and treatment efficiency suffer. The duty cycle is the ratio that expresses this balance, generally defined as on-time ÷ (on-time + off-time).

The Chemistry Behind Off-Time: What Actually Recovers During Rest

It is worth being precise about what off-time is doing physiologically, since “off-time causes recovery” is a simplification, as laid out in reviews of the cellular mechanisms of skeletal muscle fatigue. More accurately: the on-time is where metabolic “damage” accumulates, and the off-time is the window in which the muscle's own chemistry repairs that damage before the next contraction. Fatigue across a session is best understood as the net balance between what accumulates during on-

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time and what is cleared during off-time, repeated over many cycles — not something the off-time itself directly reduces or removes.

During the on-time (each evoked contraction):

- ATP and phosphocreatine (PCr) are consumed to fuel the contraction.
- Metabolic by-products accumulate — hydrogen ions (local acidification), inorganic phosphate, and extracellular potassium — all of which interfere with the excitation-contraction coupling process that links electrical activation to force production.
- Calcium released from the sarcoplasmic reticulum for each contraction is progressively less efficiently handled as cycles repeat without adequate recovery.

During the off-time (the rest interval before the next contraction):

- Phosphocreatine is resynthesized — this has its own characteristic time course, typically on the order of tens of seconds, which is part of why very short off-times do not allow full recovery.
- The Na^+/K^+ pump works to restore normal ion gradients, clearing accumulated potassium; its activity can increase more than twenty-fold above its resting rate when demand is high.
- pH and inorganic phosphate levels move back toward baseline.
- Calcium is taken back up into the sarcoplasmic reticulum, resetting the fiber for an efficient next contraction.

Practical implication: rate and intensity determine how much metabolic "cost" each contraction generates, while off-time determines whether that cost is cleared before the next contraction adds to it. A given off-time may be adequate at a low rate/intensity and inadequate at a higher one — the three parameters interact rather than acting independently, which is why off-time cannot be optimized in isolation from rate and intensity.

Two practical complications are worth flagging for documentation purposes:

- Definitions of "on-time" are inconsistent across devices and studies — some include the ramp-up/ramp-down phase in the on-time, others count only the plateau (full-intensity) portion. This makes direct cross-study comparison unreliable unless the definition is stated explicitly.
- On:off timing and ramp settings are generally believed to affect comfort and tolerability rather than being the primary driver of strength gain — intensity (amplitude), pulse width, and frequency are the parameters most directly linked to force output and fiber recruitment. Off-time's role is protective (avoiding fatigue) rather than a direct strengthening lever.

Which Parameter Drives Fatigue Most: Rate, Pulse Width, or Intensity?

Because on/off timing is only one lever for managing fatigue, it is worth situating it against the other adjustable parameters — frequency (rate), pulse width, and intensity (amplitude) — since these interact with off-time rather than acting independently of it.

A controlled comparison of NMES stimulation parameters found that lowering stimulation frequency from 100 Hz to 25 Hz reduced fatigue from 76% to 39% — a very large effect. In the same study, changing pulse duration or amplitude produced no significant change in fatigue. This points to

frequency (rate) as the dominant driver of fatigue among the three, considerably outweighing pulse width or intensity in this respect.

The likely mechanism: higher frequencies drive motor units to contract repeatedly in rapid succession without full relaxation between individual pulses, producing a denser, more metabolically demanding contraction. Lower frequencies allow more physiological-like recovery between pulses even during the “on” phase itself, independent of the off-time between contraction cycles.

- Pulse width mainly influences which fibers/axons are preferentially recruited (motor vs. sensory axons, and the orderliness of motor unit recruitment) rather than fatigue directly. Very short pulse widths (<300 µs) are associated with more random, fast-twitch-dominant recruitment, which is indirectly fatigue-prone — but this is a recruitment-pattern effect, not the same direct fatigue link seen with frequency.
- Intensity (amplitude) determines how much force is evoked and therefore how demanding each contraction is, but in the controlled comparison above it did not significantly change the fatigue percentage when frequency was held constant.

Practical implication: in the low-to-moderate rate range generally considered more fatigue-conservative (roughly 20–40 Hz, well below the 80–100+ Hz range associated with rapid fatigue onset), rate and off-time act as complementary controls — rate governs how demanding each contraction is, while off-time governs how much the muscle recovers between contractions. Neither substitutes for the other.

Does Muscle Size or Type Change the Fatigue Calculus? Trunk vs. Limb Muscles

It is tempting to assume that a bigger muscle simply fatigues more slowly, or that trunk muscles behave like a smaller version of a limb muscle. Neither assumption holds up well — what actually matters is fiber-type composition and, for surface stimulation specifically, the tissue the current has to pass through.

- Subcutaneous fat is electrically resistive, so its thickness — not muscle size — determines how much of the applied current actually reaches the muscle for a given surface intensity. A study of electrode size and placement found this effect is substantial enough to change the practical current density needed for a visible contraction. A large muscle with a thicker fat layer over it can be harder to activate efficiently than a smaller, leaner one — the opposite of what “bigger muscle” intuition would suggest.
- Trunk (paraspinal) muscles are built for a different job than limb muscles. Postural, tonic muscles such as the erector spinae and multifidus are naturally dominated by fatigue-resistant type I fibers, which sustain low-level contraction economically over long periods — quite different from a limb muscle like the quadriceps, which is built more for powerful, intermittent force and recruits a larger share of fast-fatiguing type II fibers under NMES.
- This natural fatigue-resistance is not fixed, however. In paraspinal muscle studies in scoliosis and low back pain, the muscle's fiber composition shifts toward a higher proportion of fast, fatigue-prone type II fibers compared with healthy trunk muscle — meaning a clinical population's trunk muscles may not carry the fatigue-resistance advantage that “trunk muscle” would otherwise suggest.

Practical implication: a trunk/postural muscle with normal fiber composition may reasonably tolerate a denser duty cycle than a limb muscle trained for maximal force, simply because its fibers are built for sustained low-level activity. But this advantage cannot be assumed in a muscle whose composition has been altered by the underlying condition being treated — the tolerance-based progression in Section 4.3 remains the safer way to find the right duty cycle than reasoning from "it's a trunk muscle, so it should tolerate more."

3. On:Off Ratios Reported in the Literature

Reported ratios vary by treatment goal (strengthening vs. spasticity management vs. re-education of denervated/partially denervated muscle) and by population (healthy adults, orthopedic rehab, adult neurological populations, and children with cerebral palsy). The table below summarizes representative parameters found across sources.

Population / Context	On Time	Off Time	Ratio	Frequency / Pulse Width	Source Type
Healthy adults — general NMES strengthening guidance	10 s	50 s	1:5	not specified	Narrative review (sports medicine)
General neuromuscular re-education teaching material	varies	varies	1:3 to 1:5 (or 20–25% duty cycle)	varies	PT education resource
Quadriceps strengthening, post-op / orthopedic (TKA, ACLR)	10 s	20–30 s	1:2 to 1:3	50 Hz, 400 µs	Clinical trial protocols
Quadriceps fatigue study, healthy adults	10 s	120 s	1:12	not specified	Experimental physiology study
Wrist extensor NMES, spasticity (antagonist stimulation)	20 s	20 s	1:1	35 Hz, 300 µs	Clinical trial protocol
Wrist flexor NMES + voluntary contraction, ACLR-style protocol	10 s	20 s	1:2	not specified	Comparative rehab study
Children with cerebral palsy (Carmick guidelines)	reduced with tolerance	—	narrows over time	not specified	Pediatric CP clinical guidelines (1997)

Note on comparability: because ramp-up/ramp-down inclusion in "on-time" is not always specified in these sources, ratios above should be read as approximate rather than strictly equivalent to one another.

4. Pediatric-Specific Considerations

4.1 General pediatric NMES dosing

Across pediatric neurological populations more broadly, a commonly cited minimum therapeutic dose is around 20 minutes/day, 5 days/week, for 2–6 weeks, to produce measurable functional improvement (e.g. arm function post-stroke). NMES is reported to be well tolerated across pediatric age groups, including infants, and can be applied either at rest or layered onto a functional activity.

4.2 Progressive adjustment of on/off time with tolerance

The clearest pediatric-specific precedent for adjusting on/off time over time comes from Carmick's guidelines for NMES in children with cerebral palsy: on-time can be reduced progressively as the child becomes more comfortable with the stimulation — the duty cycle is not fixed from day one, but shortened week by week as tolerance builds.

4.3 Practical Tolerance Check at Each Progression Step

Progression toward a denser duty cycle (less rest relative to work) should be achieved gradually, not in a single step — typically starting from a conservative ratio and reducing the off-time by a small increment (e.g. 2–5 s) every one to a few weeks. Each new step is effectively a short trial: whether to continue, hold, or step back should be guided by the muscle's response at that step rather than by the calendar alone. The table below is intended as a concrete, caregiver- and therapist-friendly decision aid for this purpose.

Observation at the current on/off setting	Recommended action
Evoked contraction stays stable through the full session; no increase in discomfort compared with previous sessions at this setting	Continue the planned progression (e.g. reduce off-time by the next increment on schedule)
Mild decline in contraction strength only toward the end of the session; no other new signs	Hold at the current on/off setting for a few more days before reducing off-time further
Clear decline in contraction strength during the session, combined with increased discomfort or the need to raise intensity to maintain the same visible contraction	Return to the previous (more rest) setting for a few sessions, then resume progression more slowly
Reduced contraction quality carries over from one session to the next, not just within a single session	Pause progression and reassess clinically — this pattern suggests accumulated fatigue rather than normal within-session fatigue

This decision aid operationalizes the general principle of individualized evaluation found throughout the pediatric literature. It is written to be usable by a caregiver delivering stimulation at home, not only by the treating therapist — the observations rely on what can be seen/felt during a session (contraction strength, discomfort, need to increase intensity) rather than on instrumented measurement.

4.4 Individual variability and fatigue monitoring

Multiple sources converge on the same clinical caution: pediatric response to stimulation parameters varies considerably by degree of muscle wasting/denervation and by sensory tolerance, and progression should be individualized rather than following a fixed timetable. The practical marker for whether off-time is adequate is the evoked force/contraction quality across the session — if visible contraction strength drops noticeably before the session ends, the off-time is likely too short (or on-time/intensity too high) for that child on that day.

4.5 Home-based / caregiver-delivered stimulation

Direct evidence on tSCS specifically delivered at home by parents is limited. The closest pediatric precedents are: (a) a spina bifida case report in which tSCS was delivered twice daily for 30 minutes by parents; and (b) an unrelated but instructive precedent from pediatric transcutaneous electrical stimulation for chronic constipation, where parents were trained to deliver 1 hour of daily stimulation at home for a minimum of 2 months with good adherence. Neither source addresses on/off duty cycling specifically for a home strengthening context, which remains a genuine gap in the literature.

4.6 Finding the Balance in Practice: How Pediatric CP Protocols Set Rate, Intensity, and Duty Cycle Together

The chemistry and parameter-interaction principles above raise a fair question: how is the balance actually found in practice, for children? The most direct answer comes from the cerebral palsy NMES literature, where researchers are explicit that no universally agreed guidelines exist for the exact combination of parameters in children — the balance is reached through empirical, individualized titration rather than a fixed formula. In practice, this titration follows a fairly consistent sequence across the CP literature:

- Intensity is set using a threshold-based method rather than a target %MVC: current is increased until the muscle just begins to contract, then typically doubled, and adjusted afterward only for tolerability — a practical approach given that children, especially with CP, often cannot reliably report or target a specific effort level the way adults in strengthening studies can.
- Rate is kept in a conservative, moderate range rather than pushed high for maximum force. An 8-week daily NMES program in children with CP using 30 Hz and 200–350 µs produced a 15% increase in ankle dorsiflexor muscle volume and a 20% increase in strength, with effects persisting 6 weeks after the intervention ended — evidence that a conservative rate in this range is sufficient for real strength gains in this population, not merely a fatigue-avoidance compromise.

- Behavioral familiarization precedes technical calibration. Carmick's approach introduces the sensation first on the therapist's arm, then the parent's arm, before any stimulation is applied to the child — recognizing that a child who has not first tolerated the sensation behaviorally will not give an interpretable physiological fatigue signal once treatment parameters are being set.
- Duty cycle is set pragmatically for a comfortable, rhythmical contraction rather than calculated from a formula. One documented pediatric protocol used a 5 s on-ramp, 10 s on-duty, 2 s off-ramp, and 7 s off-duty pattern chosen to produce a rhythmical muscle contraction that the child could tolerate, without the authors providing a fatigue-based justification for that specific ratio — illustrating that duty cycle in practice is often set for comfort and rhythm first, then adjusted based on observed tolerance, consistent with the tolerance-check approach in Section 4.3.

Taken together, the CP literature suggests the balance between rate, intensity, and duty cycle is not solved analytically in advance — it is reached iteratively, per child, starting from conservative and well-tolerated reference points (threshold-doubled intensity, ~20–40 Hz, generous initial rest) and adjusted based on observed tolerance and response, exactly as recommended in Section 4.3.

5. Practical Recommendations for Documenting a Duty-Cycle Protocol

- State explicitly whether ramp-up/ramp-down time is included within the quoted “on-time”, to keep any protocol internally comparable across revisions and comparable to cited literature.
- Anchor progression to an objective marker (e.g. stable evoked contraction/visible force across the full session, or absence of reported discomfort) rather than to time elapsed alone, consistent with the individualized-evaluation principle found throughout the pediatric literature.
- Consider specifying a concrete weekly step size for the off-time reduction (e.g. “decrease off-time by 5 s per week if tolerated”) to make a protocol reproducible across therapists, rather than leaving the pace of progression as a general “decrease gradually”.
- Flag the home-delivery context distinctly from clinic-delivered sessions in any written protocol — caregiver-delivered stimulation introduces monitoring/safety considerations (skin checks, recognizing fatigue, stopping criteria) that may warrant a short dedicated subsection.
- Where possible, note muscle group and joint position alongside on/off parameters — evidence in adults shows that muscle length/joint angle affects fatigue onset during NMES, which may be relevant to electrode placement notes in any protocol document.

6. Evidence Base: What Comes From Pediatric vs. Adult/General Research

It is worth being explicit about where this document's reasoning is grounded in direct pediatric data versus extrapolated from adult/general research, since the two are not equally strong forms of evidence for a children's protocol.

Pediatric-specific sources

Source	Population	What it contributes
Carmick (1997)	Children with CP	Clinical guideline: progressive on-time reduction with tolerance
Neighbors et al. 2024	Children with acute flaccid myelitis	Clinical outcomes from tSCS in a pediatric population
Case report	Infant with spina bifida	Home/parent-delivered tSCS precedent
NCT05091463 / NCT03975634	Children with spinal cord injury	Trial protocols for trunk-control tSCS in children
Archives PM&R (2023)	Children post-stroke	NMES clinical outcomes in a pediatric population
NCT07069946	Children with hemiplegia	Trial protocol combining NMES with weight-bearing exercise
Elite Learning / NMES-for-CP	Children with CP (secondary sources)	Practical framing of how parameters are set in practice
8-week NMES program	Children with CP	Concrete pediatric strength/volume outcomes at 30 Hz

Adult / general (non-pediatric) sources

Source	Population	What it contributes
Frequency/fatigue study	Not pediatric-specific	The 100 Hz vs. 25 Hz fatigue comparison underlying Section 2
TKA / ACLR studies	Adults, orthopedic rehab	Most of the on:off ratios in the Section 3 table
Ackermann et al. 2024	Adults, sports medicine	General strengthening duty-cycle guidance (1:5)
Allen, Lamb & Westerblad (2008)	Basic physiology, not population-specific	The cellular fatigue mechanisms underlying Section 2
Baker et al. (1993)	General/adult NMES practice	Foundational NMES teaching reference

Implication: the physiological foundations of this document — why off-time works chemically, and why rate outweighs pulse width for fatigue — are drawn almost entirely from adult and general physiology research, since this kind of controlled fatigue testing is rarely done in children for ethical/practical reasons. Pediatric sources are strong on whether a protocol is safe, tolerated, and clinically effective (Carmick, the CP strength trial, the SCI and stroke trials), but do not independently establish parameter-level reference points such as a specific duty cycle or frequency threshold — those are extrapolated from adult data and then applied cautiously, via the tolerance-based progression described in Section 4.3.

7. Suggested Further Search Terms

Given how little direct pediatric home-based tSCS duty-cycle data exists, the following alternative search terms may surface literature not captured by the standard “on-time/off-time” or “home-based” phrasing:

- “caregiver-administered” or “parent-delivered” + “spinal stimulation” / “NMES”
- “duty cycle” searched separately from “on-time off-time” — the two phrasings index differently on PubMed/PMC
- “denervated muscle” + “stimulation parameters” + “pediatric”, to connect duty-cycle guidance with neuromuscular conditions involving partial denervation
- Frontiers-specific search for recent pediatric transcutaneous spinal stimulation reviews, which do not always surface in the first page of PubMed/PMC results

8. Key Takeaways

Summary

• Fatigue is driven mainly by stimulation rate and intensity, not by the on:off ratio itself — off-time's role is to let PCr resynthesis, ion clearance, and calcium re-uptake catch up between contractions (Section 2).

• There is no single universal “optimal” on:off ratio. General strengthening literature favors conservative ratios (roughly 1:3 to 1:5, or more rest); lower-force, re-education-focused contexts can tolerate denser ratios such as 1:1 (Section 3).

• Progression toward a denser ratio should always be gradual and tolerance-gated — guided by observed contraction quality and comfort at each step, not by a fixed calendar (Section 4.3).

• In children, the whole parameter set — rate, intensity, and duty cycle — is typically set through iterative, individualized titration rather than a fixed formula, starting from conservative, well-tolerated reference points (Section 4.6).

• Much of the underlying physiological reasoning (why off-time works, why rate drives fatigue) comes from adult/general research rather than pediatric studies directly, since controlled fatigue testing is rarely done in children — pediatric evidence instead confirms safety, tolerability, and clinical effectiveness (Section 6).

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