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Characterization of an Algorithm for Autonomous, Closed-Loop Neuromodulation During Motor Rehabilitation

Joseph D. Epperson, PhD[1,2*], Eric C. Meyers, PhD[1], David T. Pruitt, PhD[1], Joel M. Wright, BS[1], Rachael A. Hudson, MS[1,3*], Emmanuel A. Adehunoluwa, MS[1,3*], Y-Nhy Nguyen-Duong, MS[1,3], Robert L. Rennaker II, PhD[1,2,3], Seth A. Hays, PhD[1,2*], and Michael P. Kilgard, PhD[1,3*]

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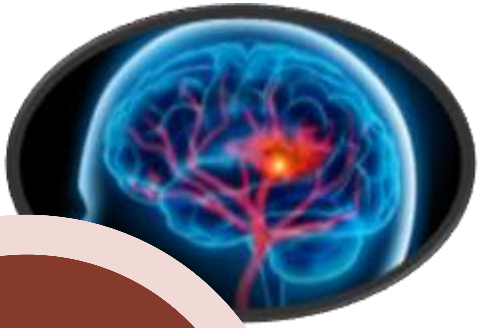
Presenter: Leo Ganser, Penghui Du, Wenxin Che

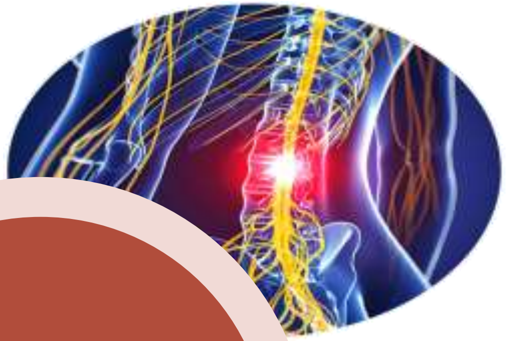
Background - Clinical Problems

- **Stroke** and **spinal cord injury (SCI)** are leading causes of **upper limb motor impairments**, significantly affecting patients' quality of life.

strokes



SCI



800,000

people per year

In U.S.

300,000

people per year

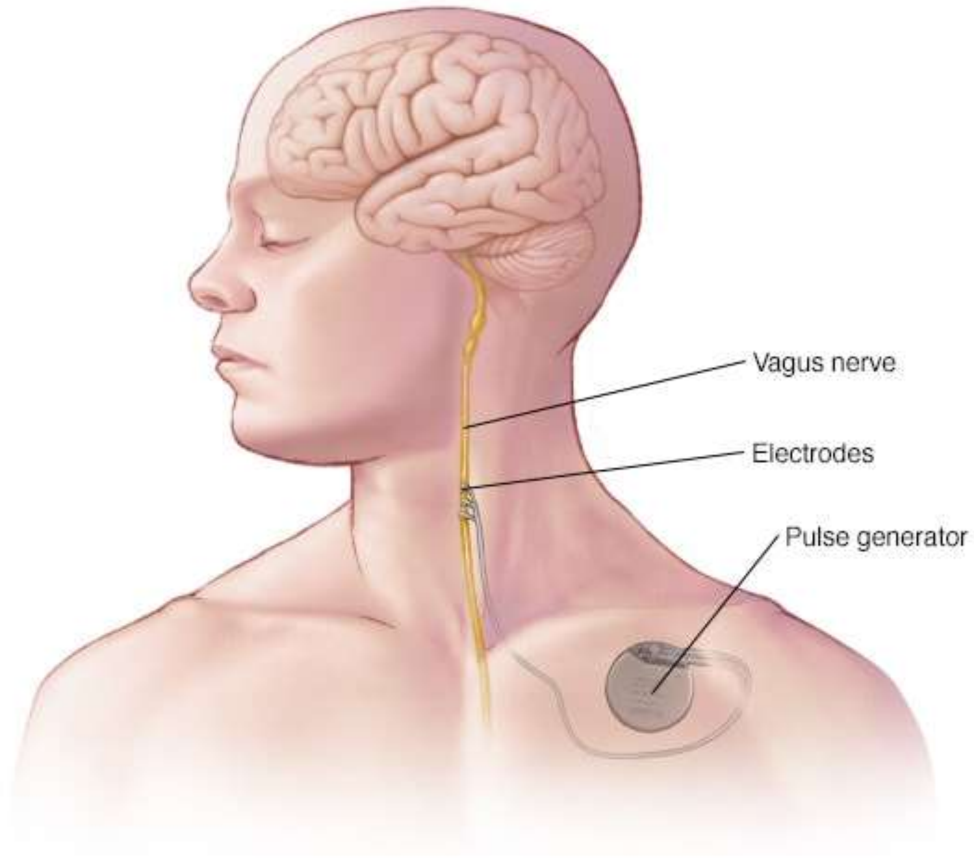
In U.S.

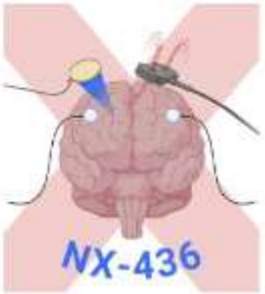
- There are approximately 800 000 strokes each year and over 300 000 people live with the effects of spinal cord injury (SCI)[1,2].
- Many survivors are left with **long-term upper limb hemiparesis**, which can lead to disability[3].

Background - Vagus Nerve Stimulation in Rehabilitation

- Vagus Nerve Stimulation (VNS), when combined with rehabilitation exercises, has emerged as a promising approach for treating upper extremity motor deficits following stroke or SCI[4,5,6].

- **Mechanism:** VNS induces a rapid release of neuromodulators, enhancing synaptic plasticity within active motor networks, which is crucial for motor recovery.





Background - Current Practice & Limitations

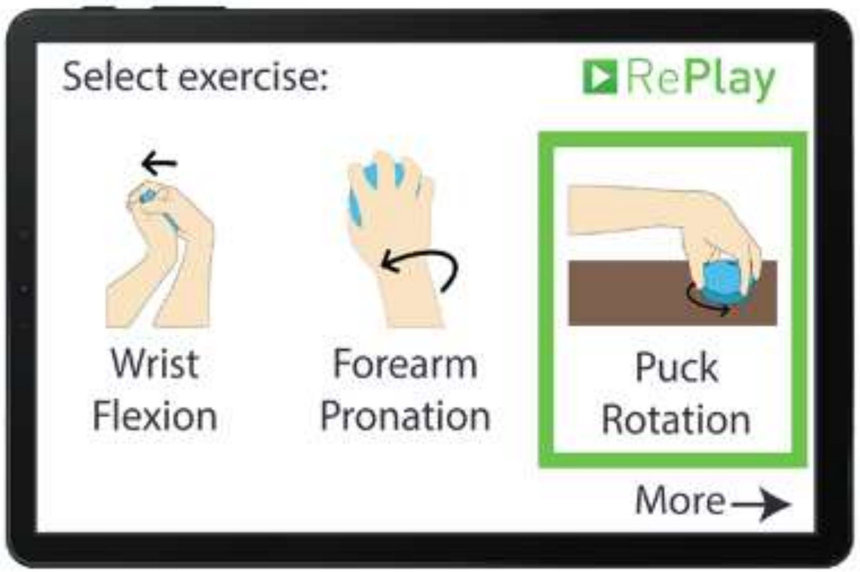
1. Currently, VNS is delivered through an implanted device, and a therapist **manually** triggers the stimulation during exercises by pressing a button.

2. **Timing** is crucial: Studies in animal models and human trials have demonstrated that **immediate** VNS yields significantly better recovery, compared to delayed VNS[7].

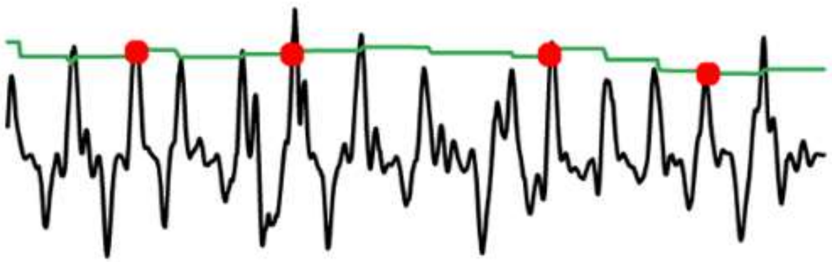
3. **Stimulating during the best movements** is crucial**:** VNS delivered during rehabilitation fail to be effective if not concurrent with the "**best**" movements[8].

Background - Overview of Proposed Solution

- They developed three algorithms to **automate** VNS delivery, replicating the therapist's role in timing the stimulation, and analyzed which approach was the most effective.



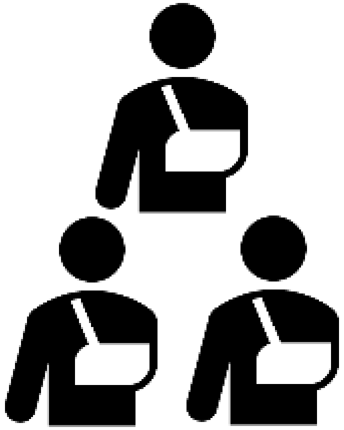
Signal recording during rehabilitation movements



Signal processing and algorithm analysis

Trigger VNS at proper timing

Methods – Subjects and Devices



32 Patients

14 with stroke

18 with cervical spinal cord injury (SCI)

Performing tasks on RePlay[9]

A game-based, unsupervised system for rehabilitation

Vagus Nerve Stimulation using ReStore[10]

An implantable wireless nerve stimulator system with no battery. Can be programmed wirelessly to deliver stimulation.

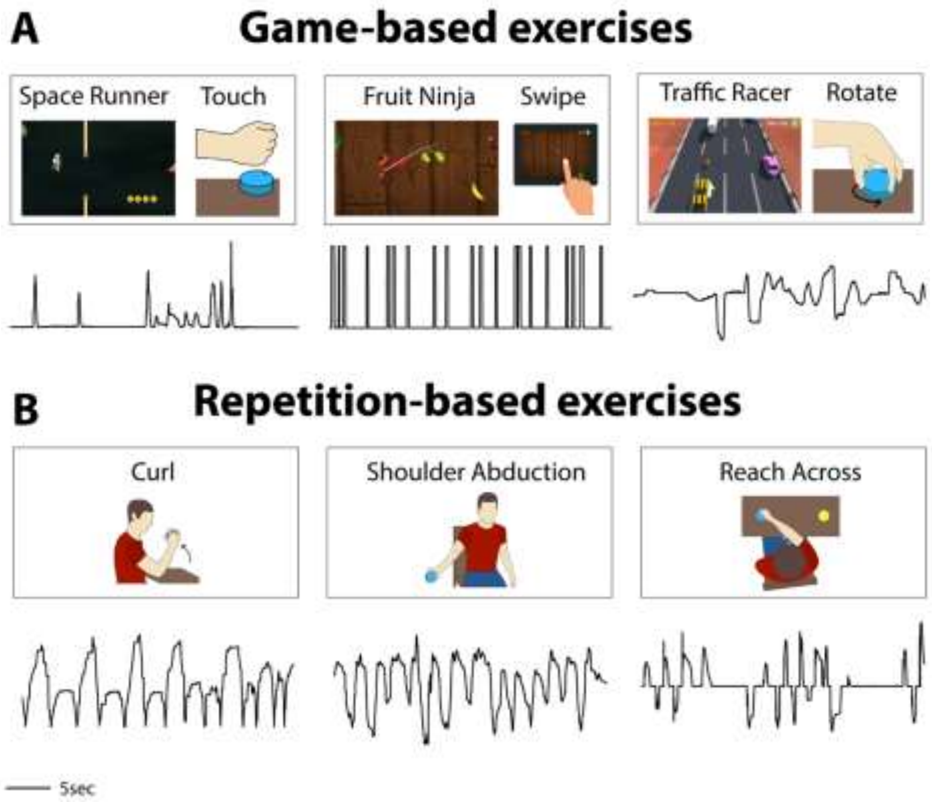
> “Most commercially available nerve stimulators include a battery and wire leads which often require subsequent surgeries to address failures in these components”

Methods – Rehabilitation Tasks

9 miniatured sensors: (Record angle, force, and distance)

- FitMi handheld motion controller (Flint Rehab, California) – For repetition-based exercises
- ReCheck system – For playing games on an Android tablet[11].
- Tablet's touchscreen – For fruit ninja.

7 Tasks:

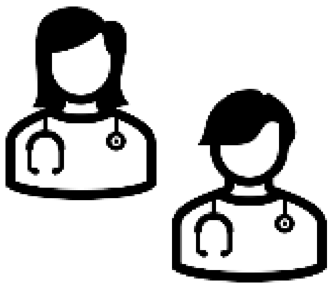


Game-based exercises. Less boring and easy to do at home

Traditional, well studied exercises

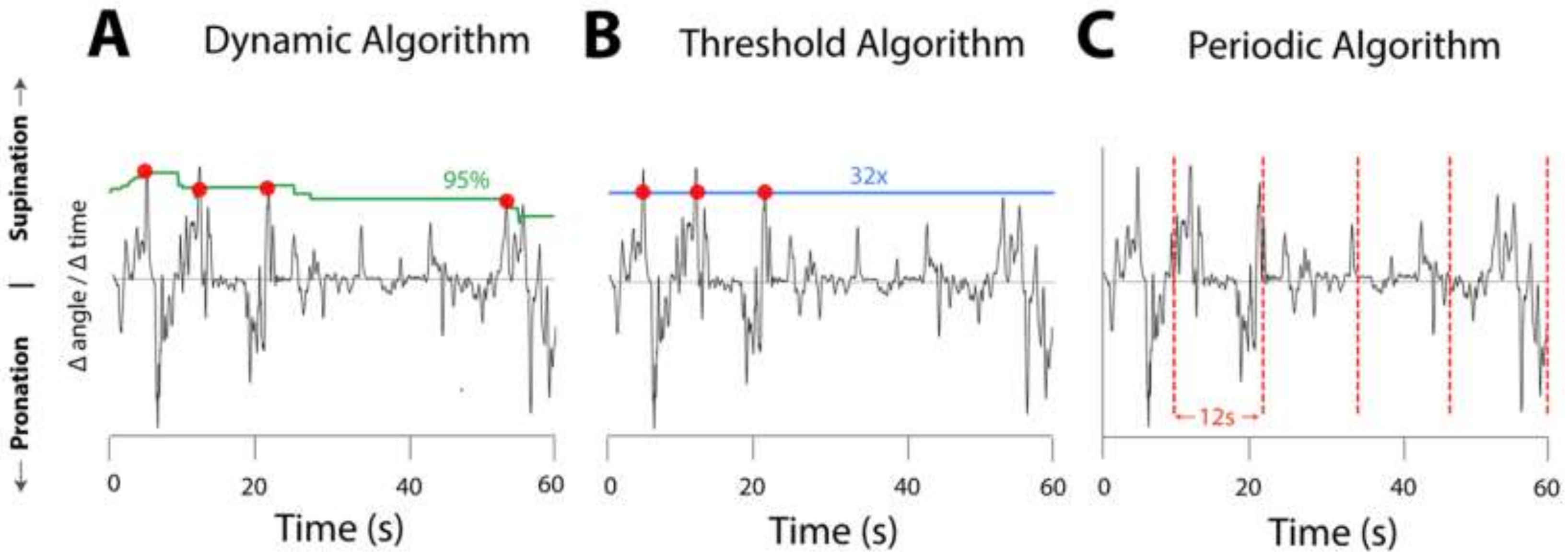
Methods – Picking Movements & Deliver Stimulus

Manual Stimulation



Delivered by
trained therapist

Automatic Stimulation



Minimum Inter-Stimulus-Interval (ISI): 5 seconds

Methods – Signal Preprocessing

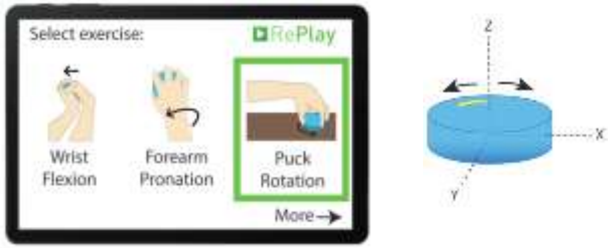
Movement selection and capture

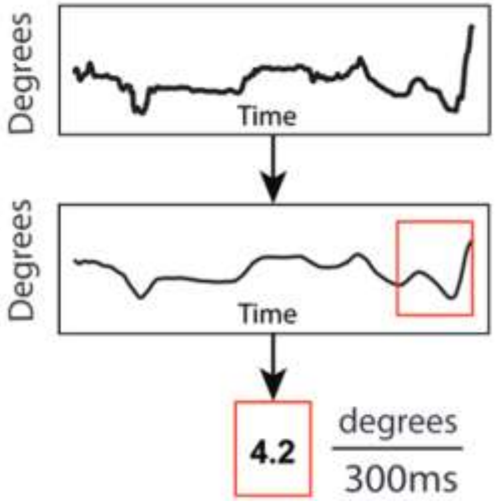
Smooth the recorded movement signals
(300ms kernel. Large movements ~300ms to complete)

Calculate the temporal gradients.

Calculate mean gradient over 300ms time window
=> A single value for average rate of change
(of angle / force / distance)

Exclude signals below a threshold to separate movement from noise





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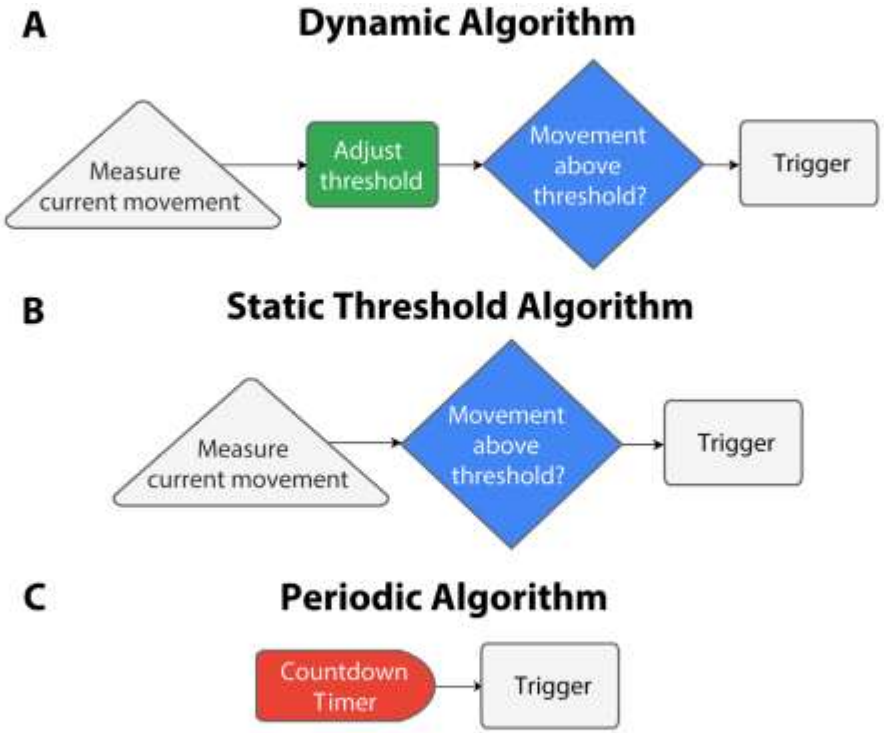
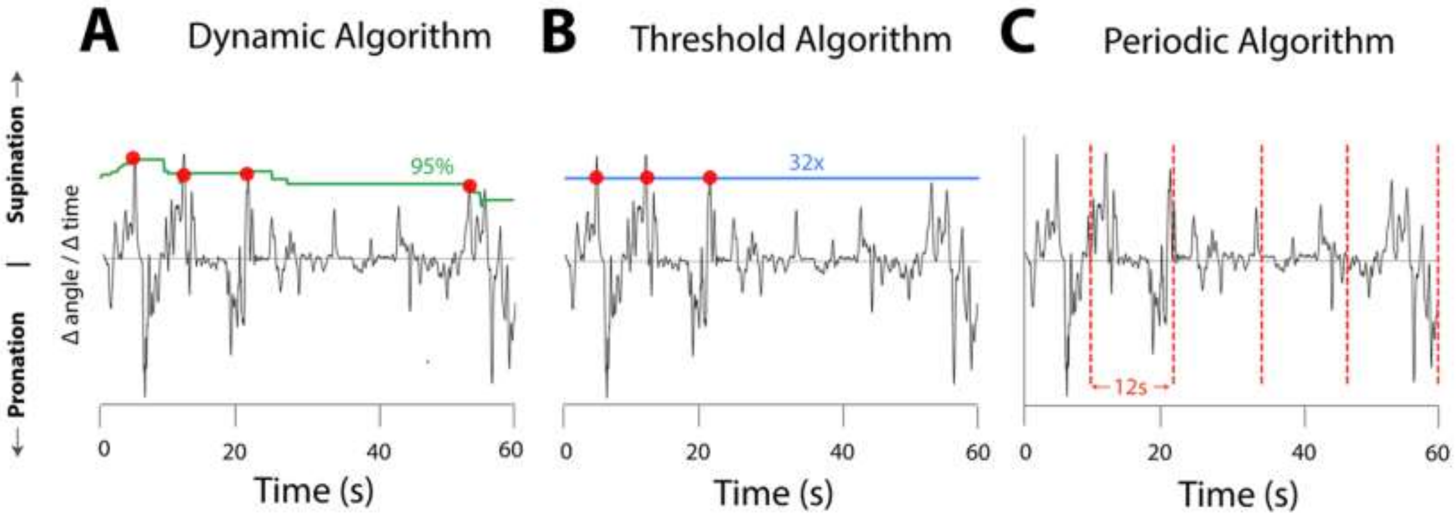
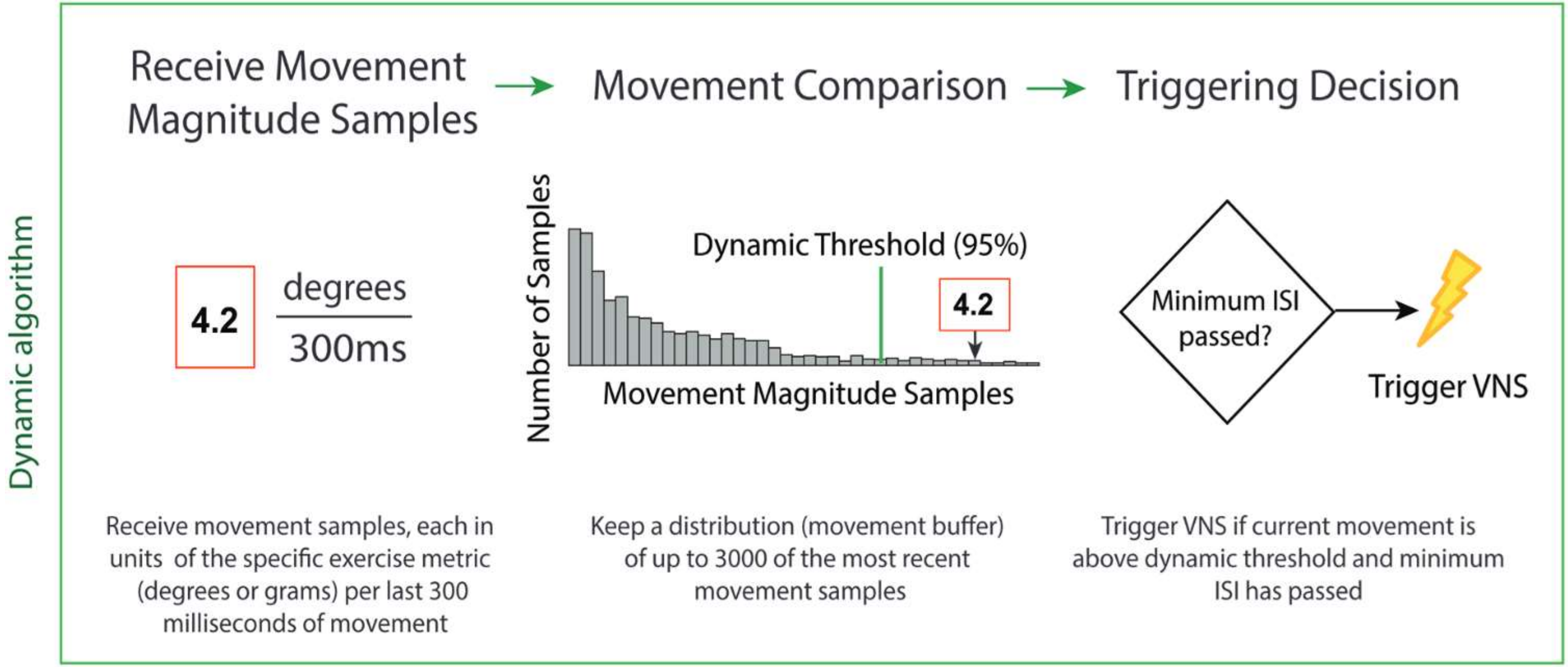
Methods – Automatic Stimulation

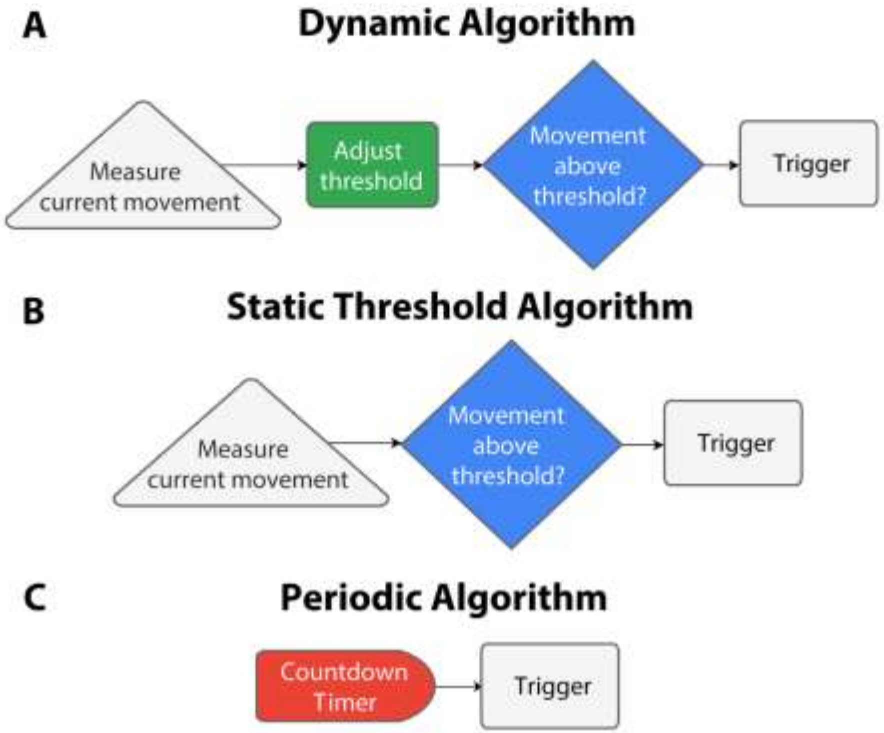


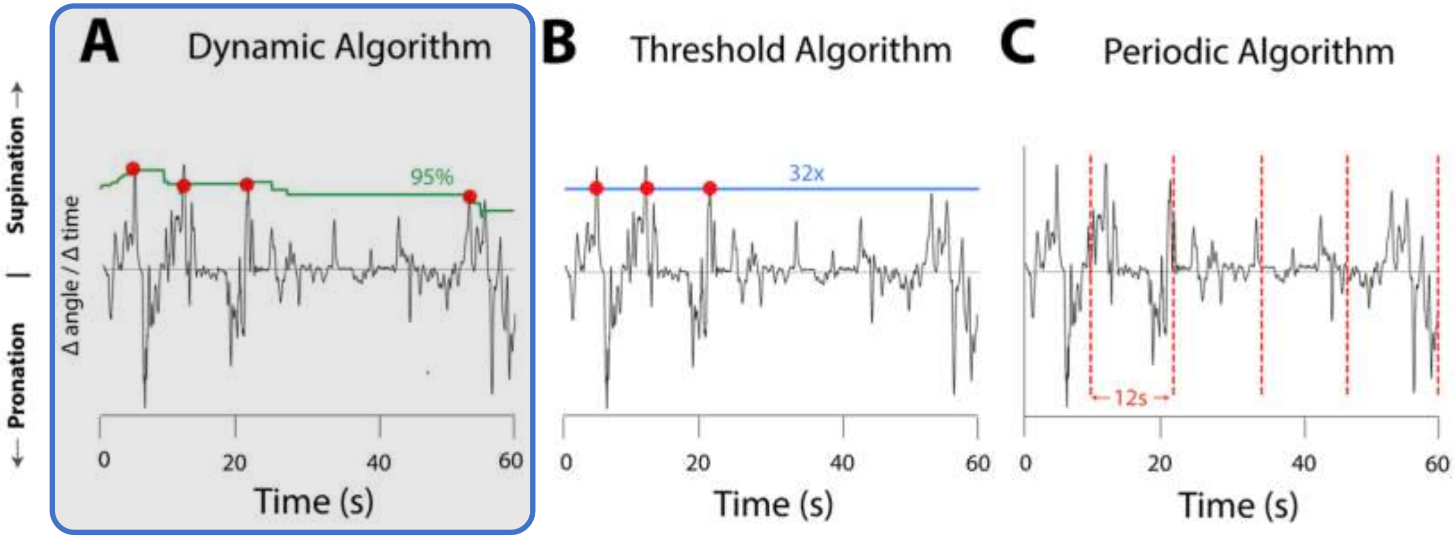


Methods – Signal Preprocessing



Methods – Automatic Stimulation





Performs the best!

Results – Algorithm comparaison

Algorithms	Selectivity	Consistence over different exercices session	Complexity
Dynamic	97%	100% of sessions had VNS → Adjustable	high
Static	64%	29% → No VNS 43% → < 95% selectivity	medium
Periodic at 12 sec interval	34%	NA	very low

Results – Algorithm comparaison

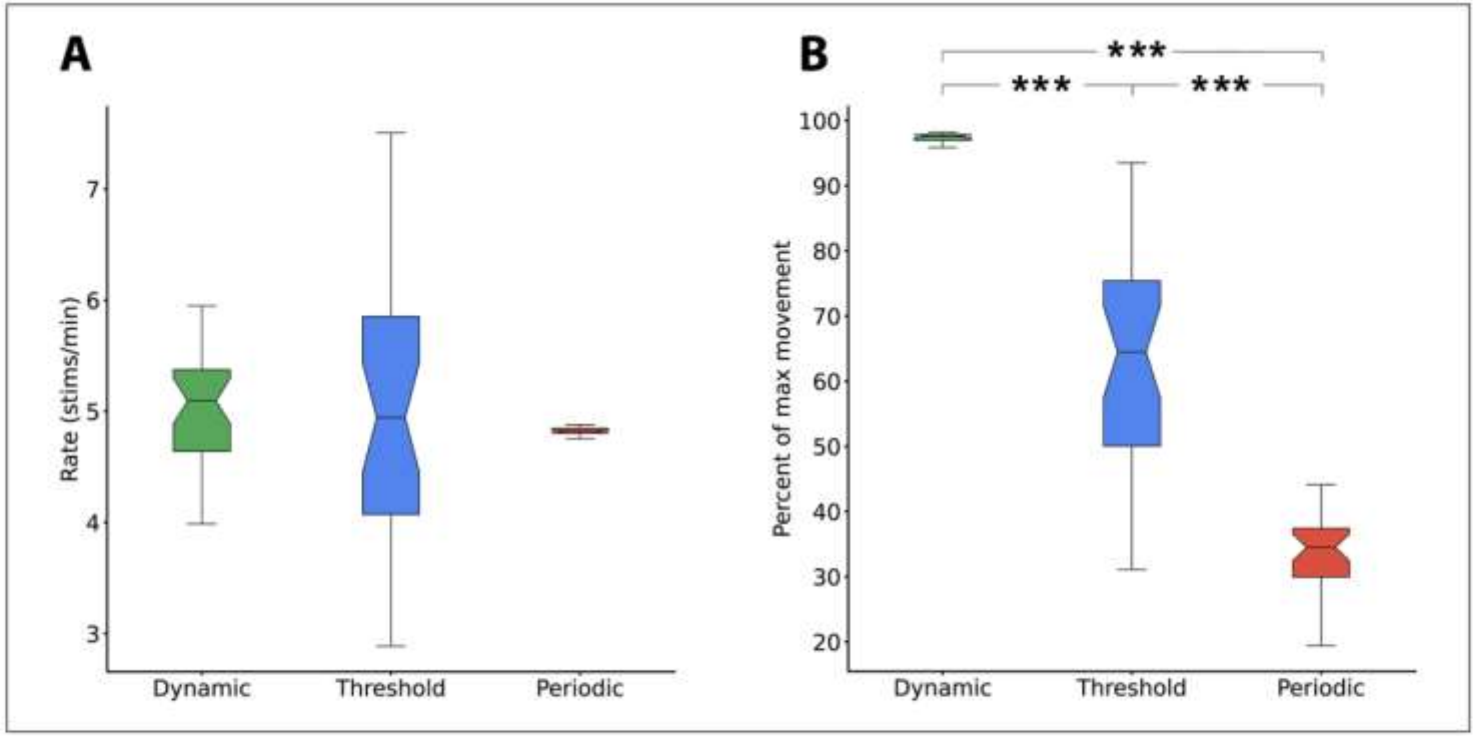


Figure 5. The dynamic algorithm yields the most robust selection of large movements and a reliable triggering interval. (A) The periodic algorithm produced consistent triggers every 12 seconds for a rate of 5 stims/minute. Variance of the periodic triggering rate seen here is from gameplay times not divisible by 12. The static threshold algorithm produced a median triggering rate of 4.94 (IQR = 1.78) stimulations per minute with considerable variance. The dynamic algorithm produced a median triggering rate of 5.09 (IQR = 0.74) stimulations per minute with moderate variance. No significant differences between median rates were observed. The notched boxes in each plot represent 1160 exercise sessions and include all controllers, games, and participants. Notches represent a 90% CI of the median. (B) The quality of the movements selected by the algorithms are represented as the percent of maximum movements during each exercise. The periodic algorithm triggered VNS on 34.50% (IQR = 7.47) of maximum movement. The threshold algorithm triggered VNS on 64.50% (IQR = 25.38) of maximum movement. The selective algorithm triggered VNS on 97.61% (IQR = 0.88) of maximum movement.

Results – Dynamic Algorithm VS Therapist

- The dynamic algorithm performs really well compared to the periodic algorithm and the therapist.
- Surprisingly, this result also shows that the therapist is not doing so much better than the periodic algorithm

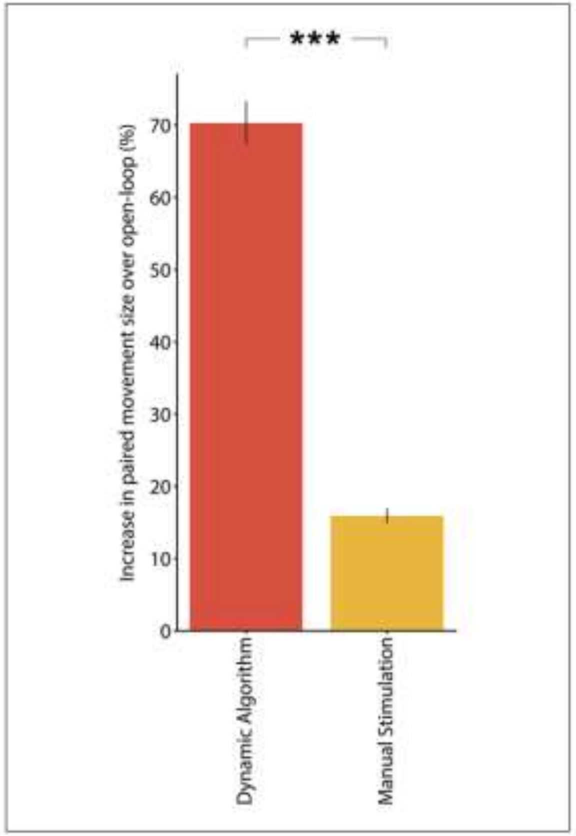


Figure 7. The dynamic algorithm selects larger movements than a trained observer. During upper limb physical therapy with RePlay and ReCheck, the dynamic algorithm triggered stimulation on movements that were $54.38 \pm 2.97\%$ larger than movements selected by a trained physical therapist (unpaired 2-tailed *t*-test, $P = 1.77 \times 10^{-74}$). We individually normalized the movement data by calculating the average paired peak size within $\pm$ 1 second of periodic stimulations at 12 second intervals throughout the therapy session. The dynamic algorithm and the periodic algorithm were applied in post-hoc analysis and the manual stimulations were conducted in real time.

Discussion

Limitations:

- Very simple algorithm
- A lot of data for exercice sessions but only 32 patients, 1160 exercices sessions
- Maybe some bias by not presenting an other relevant algorithm
- Sensor in single dimension → Not very complex movements

Open question

- How good are therapists evaluating the best movements? Or how good are the sensors at evaluating the best movement

- To what extent, telereabilitation will improve the recovery process ?

- Getting approval for this unsupervised device ?

Take home message

What is the novelty ? **The ALGORITHM**

→ No more manual VNS

→ First step toward telereabilitation

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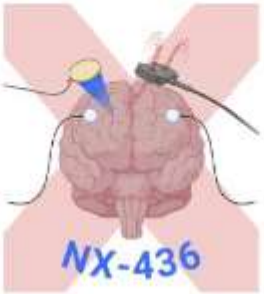

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