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WHEN A MECHANICAL CONTINUUM REQUIRES A DISCRETE CONTROL

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INTRODUCTION

Participants anticipate the effects of an elastic force field on the fingertips. Mechanically, this dynamics is only parameterized by its stiffness, ranging continuously from smooth forces to very high impact-like profiles.

Recently, we showed that the CNS does not attempt to predict the exact time course of the force profile after impact but instead, it applies a default strategy consisting in gripping harder about 60ms after impact. This strategy optimizes object stability by regulating mechanical parameters including stiffness and damping through grip force. Interestingly, grip force control in extreme elastic forces (smooth vs. impact) exhibits structurally different mechanisms which contrasts with the underlying continuous dynamics.

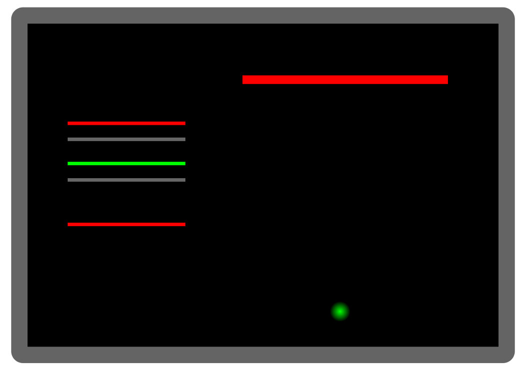
We designed an experiment to show that participants switch from one control to another upon a threshold stiffness value.

CONCLUSION

Grip force regulates hand impedance at two levels. **High level:** Baseline and peak grip forces are adjusted asymmetrically in ascending (decrease and plateau) and descending blocks (constant level of grip force). **Low level:** Impedance is regulated by modulating the occurrence of grip force max in function of expected force onset, and therefore stiffness.
This modulation occurs up to a certain threshold which marks a discrete transition contrasting with the underlying mechanical continuum.
A compromize is found between dissipation of energy through moderate impedance and controlability through larger impedance.

METHODS

Materials



A robot equipped with a grip force transducer was controlled in real time to generate elastic force fields. Feedback position was given as a green sphere on an LCD screen.

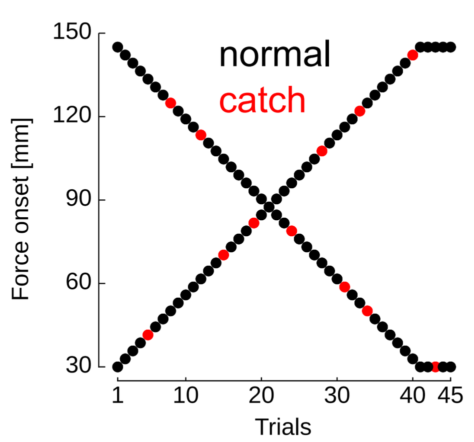
Experimental procedure

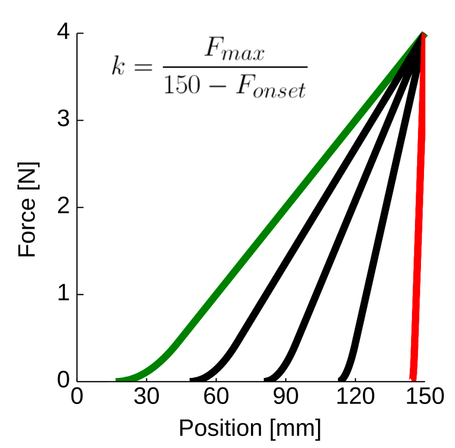
Six participants produced back-and-forth tapping movements to a visual target (red bar). Velocity to the target was normalized to

B1 B2 B3 B4 B5
Ascending

B6 B7 B8 B9 B10
Descending

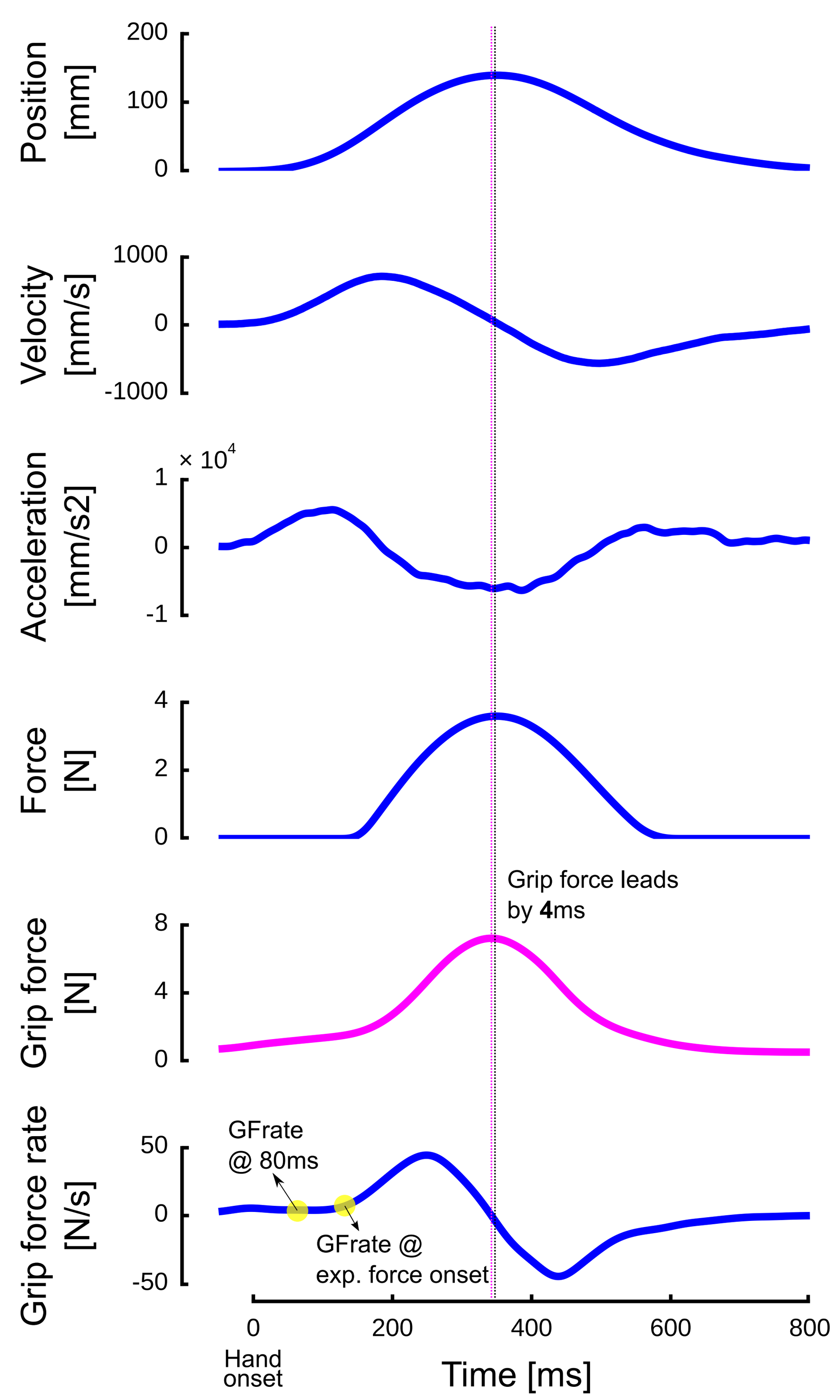
Force onsets linearly increased from starting position in ascending blocks and decreased in descending blocks, leading to a modulation of stiffness. Catch trials in 13% of trials.





TYPICAL TRIALS

Low stiffness
(40N/m, force onset at 50mm)



Position increased up to target (150 mm) and decreased to baseline

Velocity was double-peaked (to and from target).

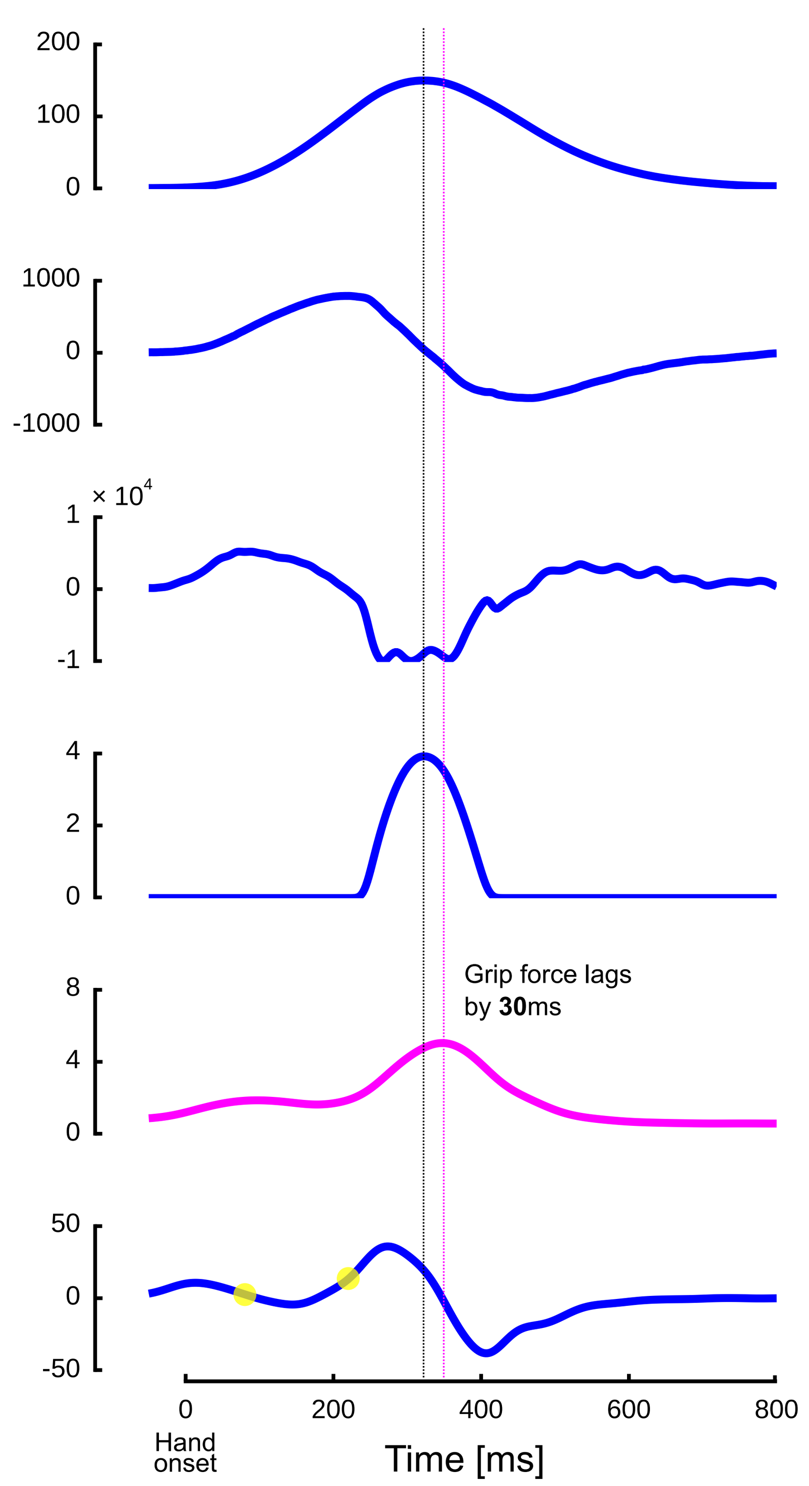
Acceleration showed max after hand/target onsets and min when force was largest.

Force increased linearly with position up to max 4N, slowly or quickly. Exact time-course depended on velocity.

Grip force raised in anticipation of the force and reached a max slightly before (low stiffness) or after (high stiffness) the peak force.

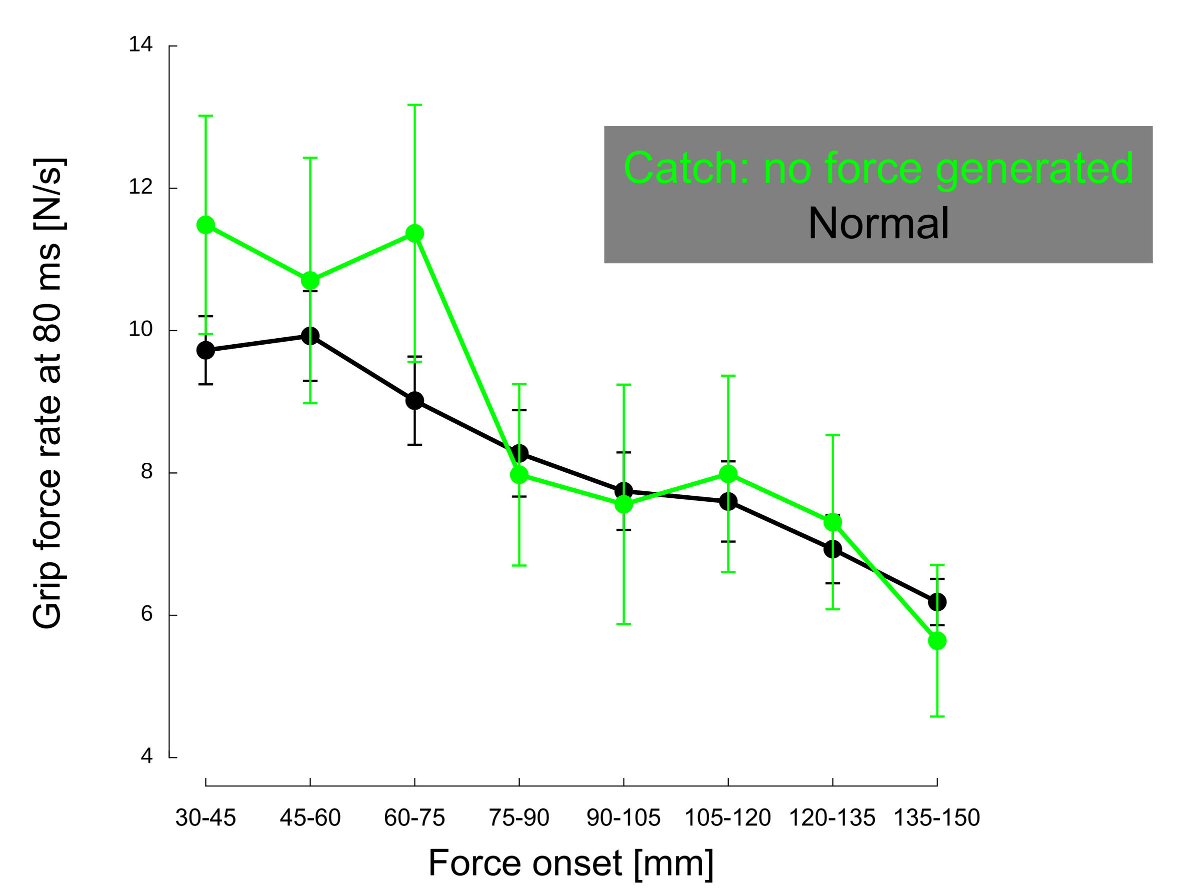
Grip force rates at 80ms and at expected force onset were used to assess the degree of pre-programming.

High stiffness
(133N/m, force onset at 120mm)

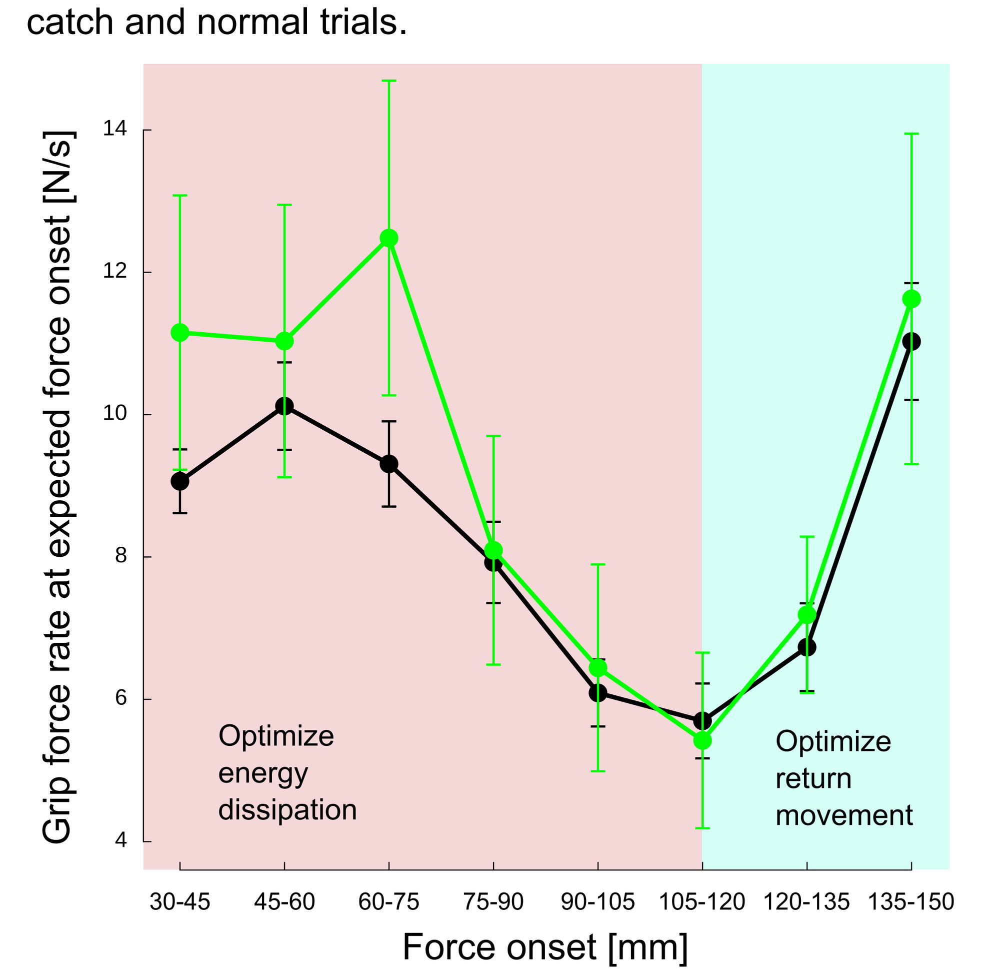


OPTIMIZATION OF IMPEDANCE

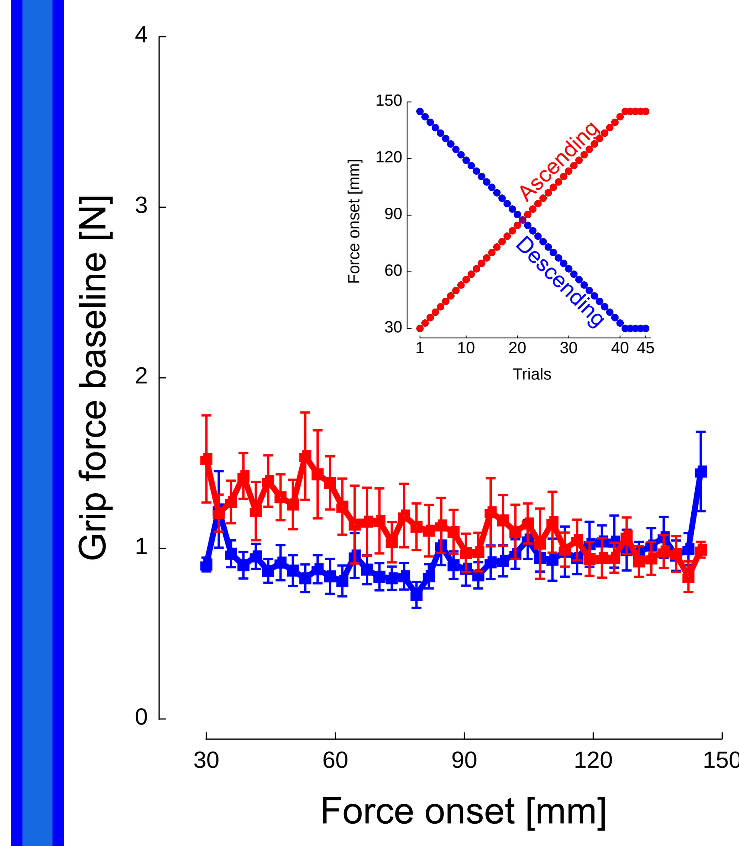
Grip force rate decreases with **expected stiffness** in normal and catch trials. Earliest force onsets were found at 100ms after movement start.



Grip force rates at **expected force onset** times decrease 50% down to a minimum reached for stiffness corresponding to ~85N/m, then increase again. No difference between catch and normal trials.



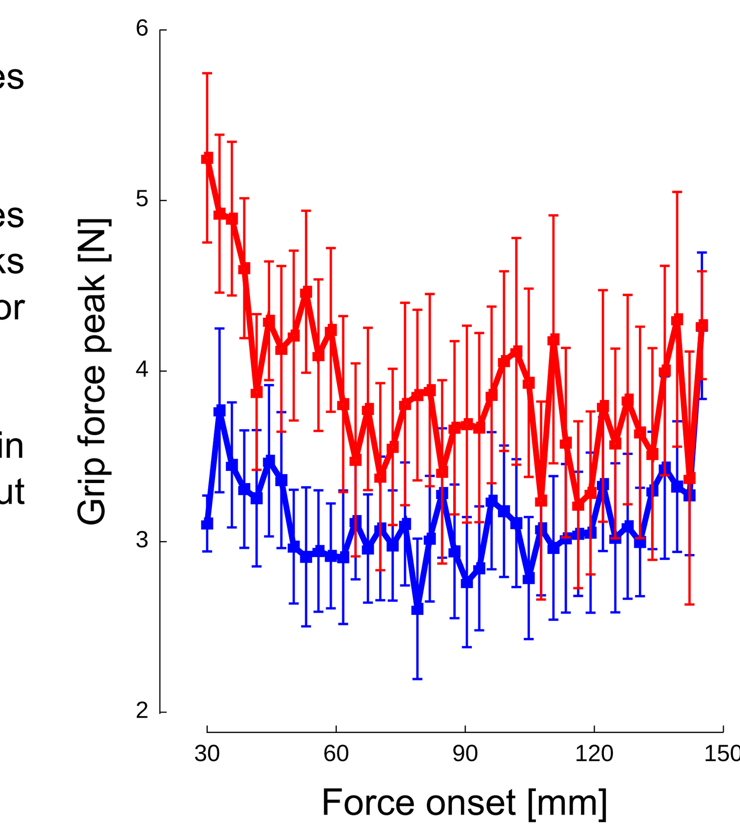
GLOBAL REGULATION OF IMPEDANCE



Grip force regulates hand impedance.

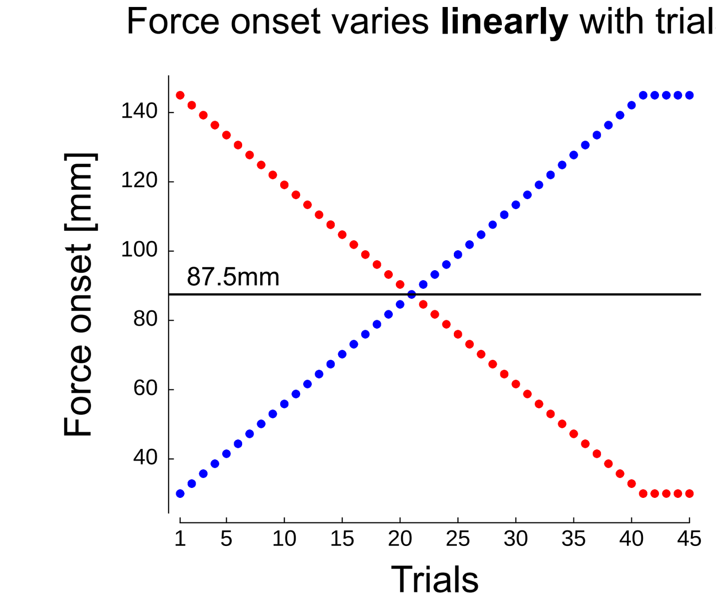
GF baseline decreases in ascending blocks reducing impedance for larger stiffness.

GF peaks are larger in ascending blocks but stabilize after 15 trials.

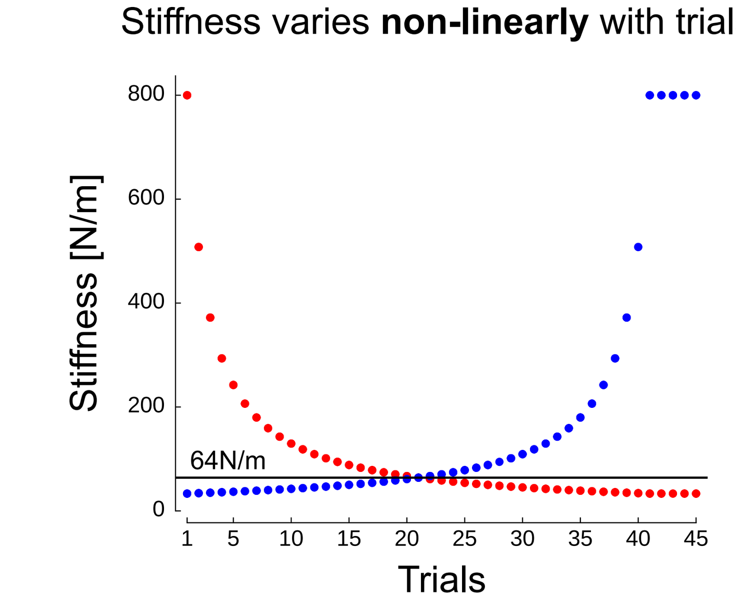


FINE REGULATION OF IMPEDANCE

Force onset varies **linearly** with trials.

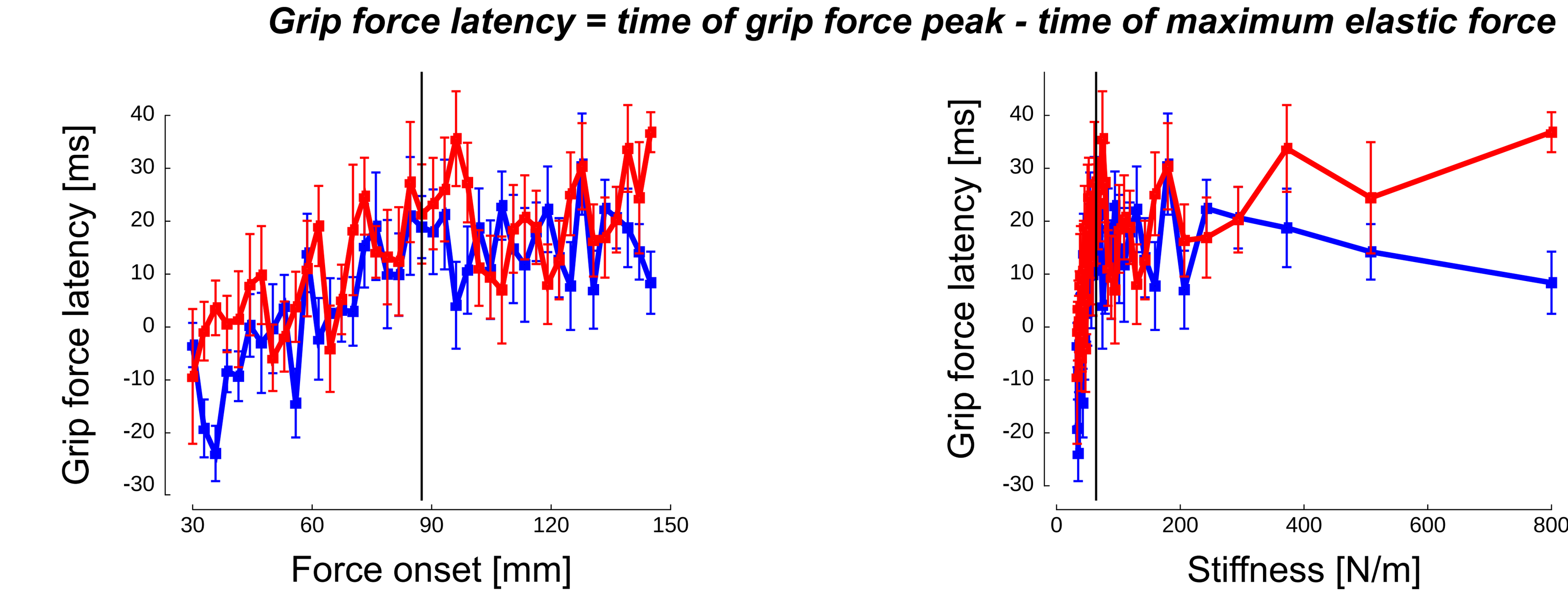


Stiffness varies **non-linearly** with trials.



Grip force peaks lead the maximum elastic force peaks in soft trials but lag these events in stiff trials. Latencies co-vary with force onsets up to some value (87.5mm) leading to a threshold of stiffness (64N/m). Impedance is regulated by modulating the occurrence of GF max in function of expected force onset.

Grip force latency = time of grip force peak - time of maximum elastic force



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