Single and multiscale entropy - Regularity and complexity of human movement

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Content

- Nonlinear mathematical tools
- Entropy
- Single scale entropy
  - Sample entropy
  - Methodological consideration (the short version)
  - Other single scale entropy measures
  - Interpretation
  - Examples from human movement research
- Multiscale entropy

- Methodological consideration (the long version)

Nonlinear mathematical tools for human movement research

Entropy (e.g. sample or approximate)
- Regularity/predictability

Multiscale entropy
- Complexity/regularity on multiple time scales

Entropic half-life
- Signal time dependency

Detrended fluctuation analysis
- Statistical persistency or anti-persitency

Surrogation analysis
- Fluctuation nature origin

The largest Lyapunov exponent
- Exponential rate of divergence/convergence in state space

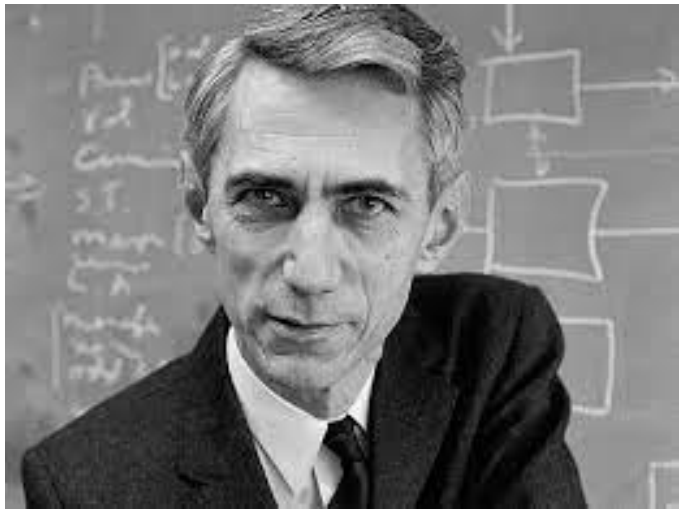
Correlation dimension
- Fractal dimensionality

Recurrence quantification analysis
- Quantification of recurrence patterns

Statistical persistence decay
- Strength of signal time dependency

Entropy

- The amount of uncertainty regarding the order in a signal.
- First develop in classical thermodynamics.
- Applied to information theory by Claude Shannon.
- A measure of the amount of information that is lost before reception.
- Approximate entropy (ApEn) was introduced in 1991 by Steven M. Pincus for quantification of regularity/complexity in biological signals.
- Sample entropy (SaEn) was later introduced to correct of calculational bias in ApEn by Richman and Moorman (2000).



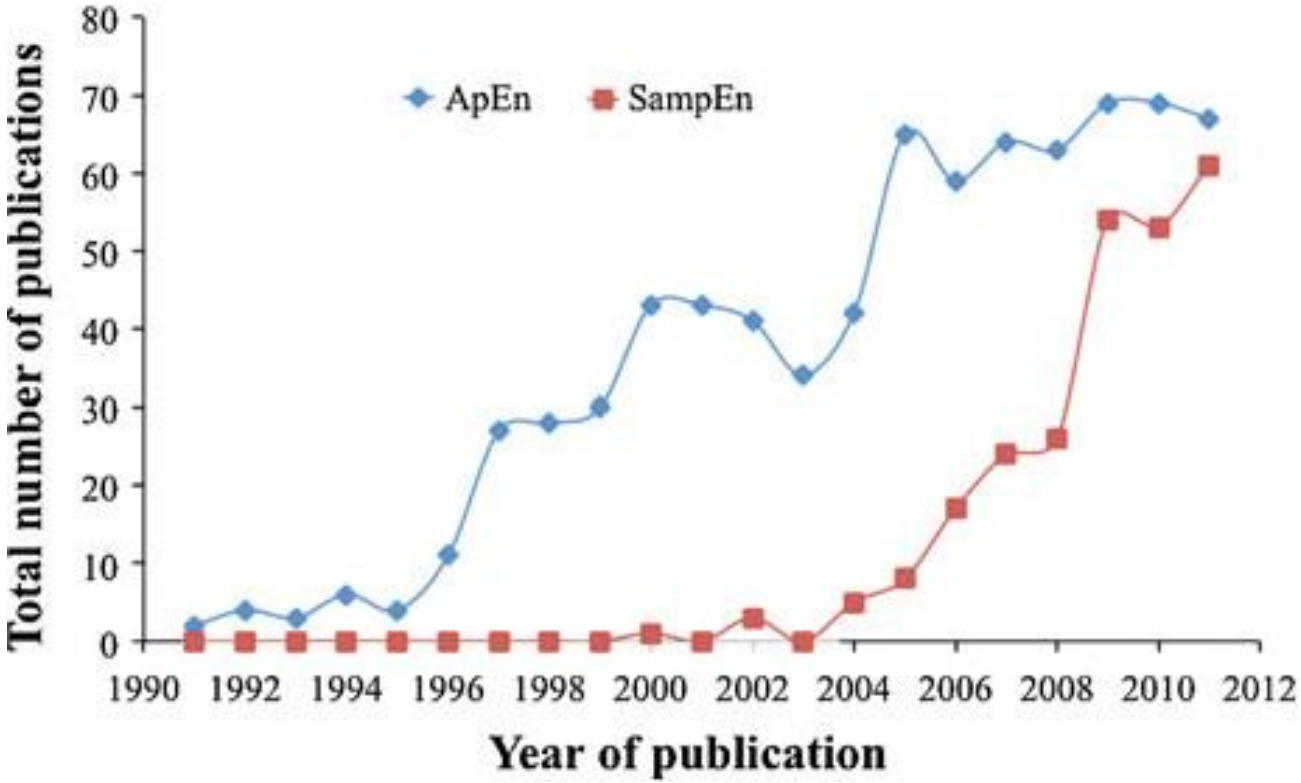
Claude Shannon
1916-2001

Sample entropy

- Approximate entropy year 2022:
  - 248 pubmed hits

- Sample entropy year 2022:
  - 810 pubmed hits

2022 pubmed search ApEn/SaEn
- Gait = 2/18
- Movement = 14/53
- Postural control = 6/27
- Motor control = 9/20



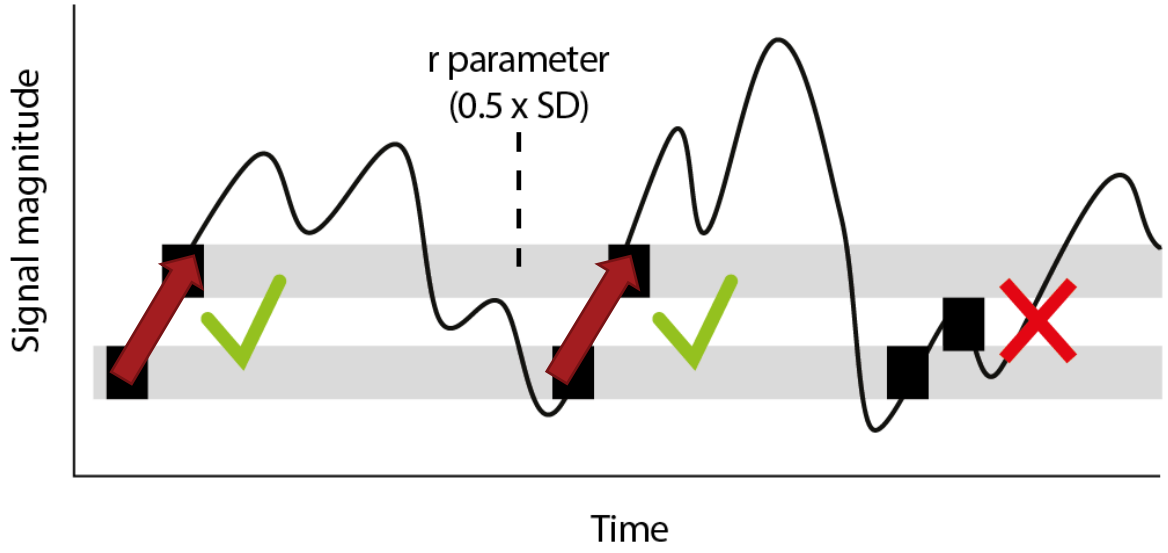
Yentes et al. 2012

Sample entropy

- 'The negative natural logarithm of the conditional probabilities that two sequences similar for m points remain similar at the next point' Richman and Moorman 2000

$$SaEn(m, r, N) = -\ln\left[\frac{A^{m+1}(r)}{B^{m}(r)}\right]$$

- **N** is the number of data points in the time series
- B is the number of similar vector lengths (**m**) falling within the tolerance limit (**r** x standard deviation of the time series)



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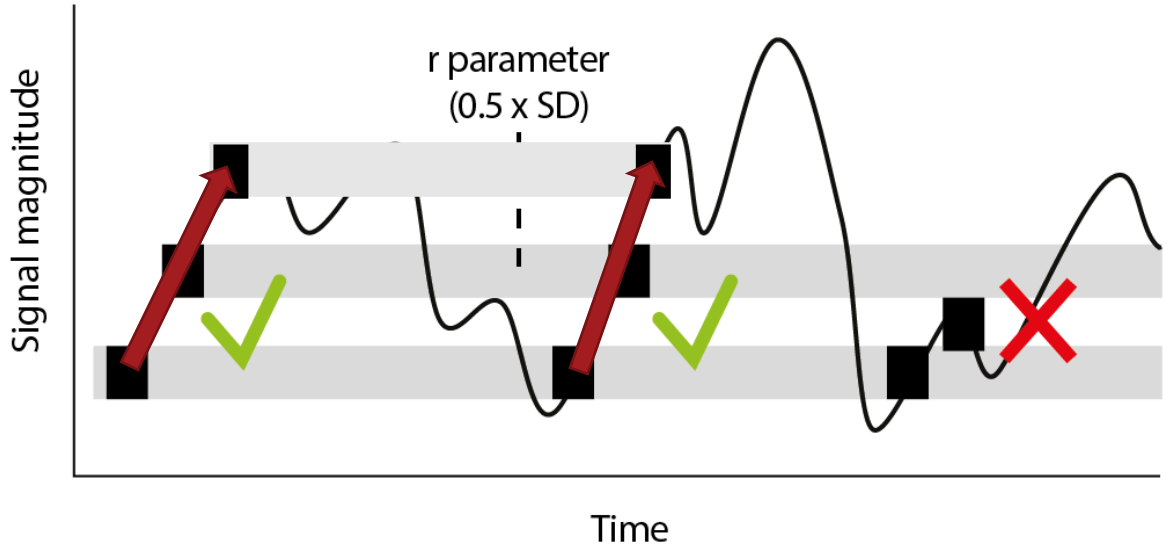
- A is the number of similar vector lengths (**m**+1) falling within a relative tolerance limit



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$$SaEn(m, r, N) = -\ln\left[\frac{A^{m+1}(r)}{B^{m}(r)}\right]$$

- The higher A/B ratio the more vectors remain similar at the next point in the time series and the lower the sample entropy =>
  - **The more predictable pattern exists within the time series (high regularity)**
- The lower A/B ratio the fewer vectors remain similar at the next point in the time series and the higher the sample entropy =>
  - **The less predictable pattern exists within the time series (low regularity)**
- SaEn values between ~0 and infinite

Sample entropy – methodological considerations

- Discrete or continuous data
- Sampling frequency
- Observation time
- Filtering of data
- Input parameters and their relative consistency

Sample entropy – relative input parameter consistency

- Many (if not all) nonlinear mathematical tools have input parameters.
- Changing the input parameters affects the outcome of the calculation.
- Any observed biological phenomenon should remain the same when changing input parameters (within a range) to be considered valid.
  - Differences between tasks
  - Differences between groups
  - Differences before/after intervention

Always test and report the relative parameter consistency of your data!

- For sample entropy: m, r and N

Other single scale entropy measures

- Correlation entropy
- Permutation entropy
- Increment entropy
- Symbolic entropy
- von Neumann entropy
- Fuzzy entropy

Interpretation of sample entropy

Proc. Natl. Acad. Sci. USA
Vol. 88, pp. 2297–2301, March 1991
Mathematics

Approximate entropy as a measure of system complexity

(statistic/stochastic processes/chaos/dimension)

STEVEN M. PINCUS

- Approximate entropy has historically been used to quantify complexity.
- Low values meaning low complexity.
- High values meaning high complexity.

- Should sample entropy be used for quantification of complexity as well?

Interpretation of sample entropy

Complexity definition:

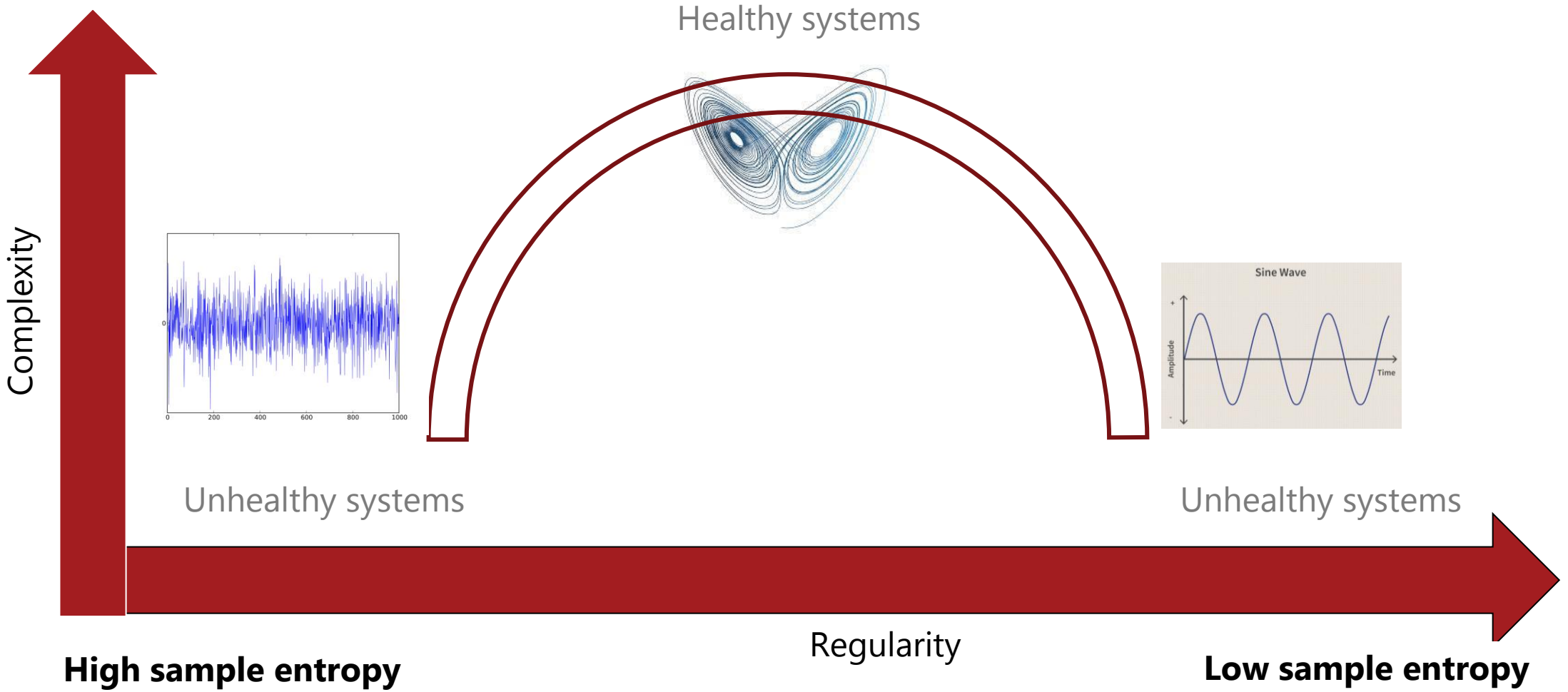
- "We define complexity in human movement as a system that (1) originates from a deterministic origin, (2) cannot be broken down into fundamental components – 'infinitely entangled', and (3) 'operates across multiple spatial and temporal scales' – structural richness."

Yentes and Raffalt 2021, based on Costa et al. 2005 and Delignieres and Marmelat 2012

- Can single-scale entropy capture this characteristic?

- Sample entropy is a measure of regularity.
  - Low values meaning high regularity (periodic behavior)
  - High values meaning low regularity (random behavior)

Interpretation of sample entropy in a theory



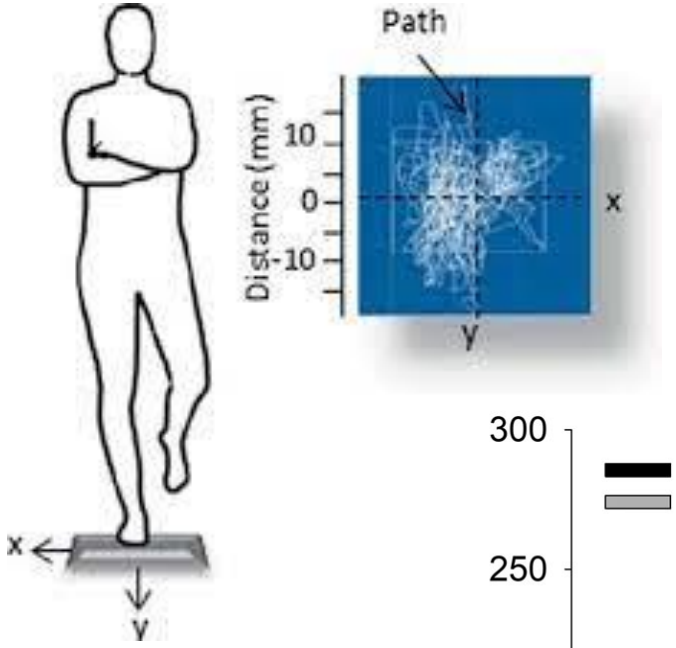
Stergiou et al. 2006

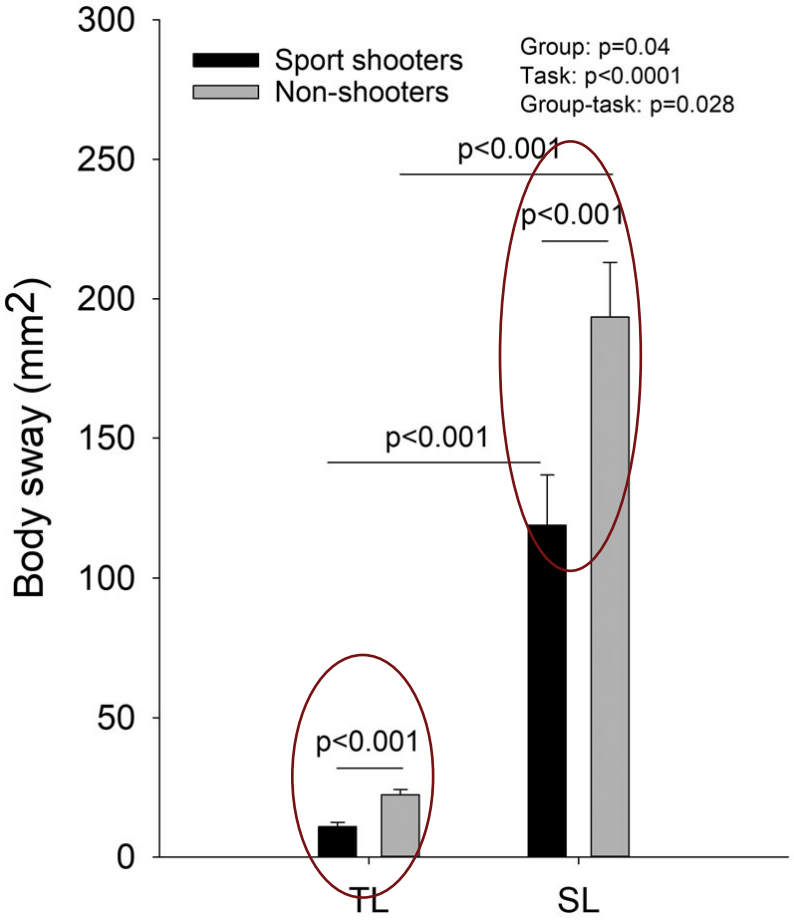
Examples of sample entropy in human movement research

- Upright standing in:
  - Sport rifle shooters
  - Individuals with transtibial amputation

Postural control of experts

- Elite sport rifle shooters vs non-experts
- Upright standing on a force platform
- Two-legged vs single legged stance
- Quantified
  - Body sway of the center of pressure
  - Regularity of the center of pressure
- Sport rifle shooters had less body sway than non-experts during both tasks

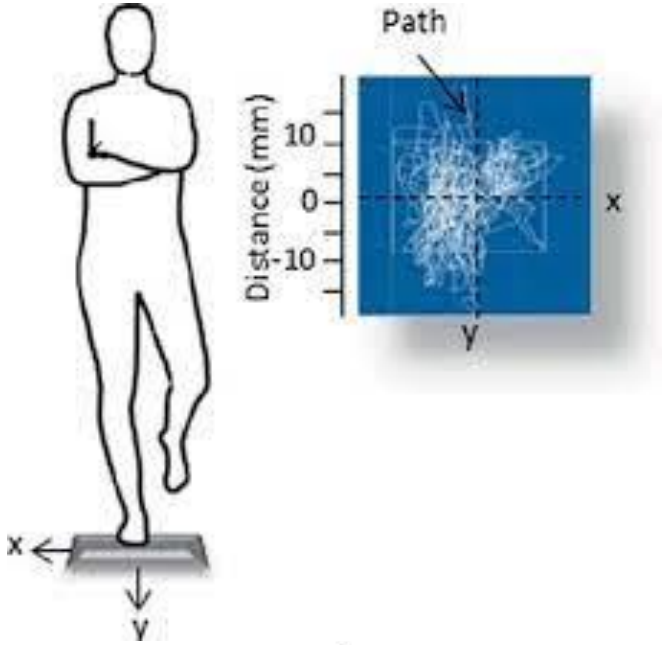


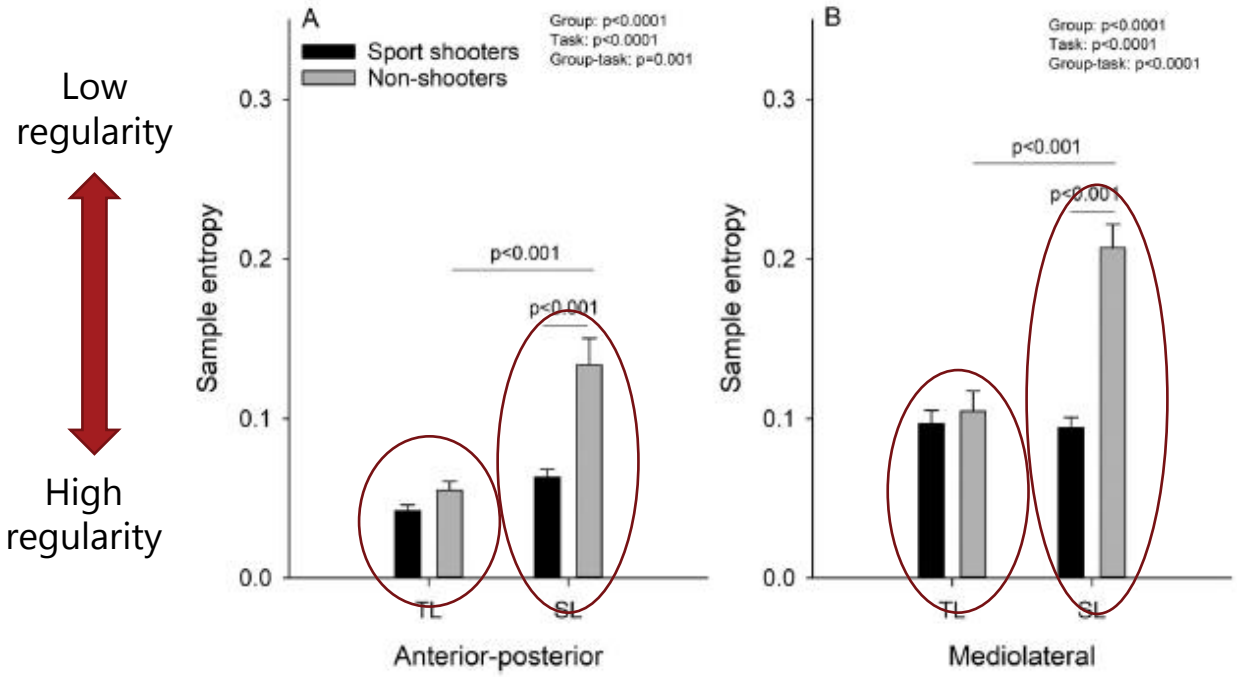


Raffalt et al. JMB, (2020)

Postural control of experts

- Elite sport rifle shooters vs non-experts
- Upright standing on a force platform
- Two-legged vs single legged stance
- Quantified
  - Body sway of the center of pressure
  - Regularity of the center of pressure
- Sport rifle shooters had less body sway than non-experts during both tasks
- Sport rifle shooters had more predictable movements compared to non-experts during single legged stance





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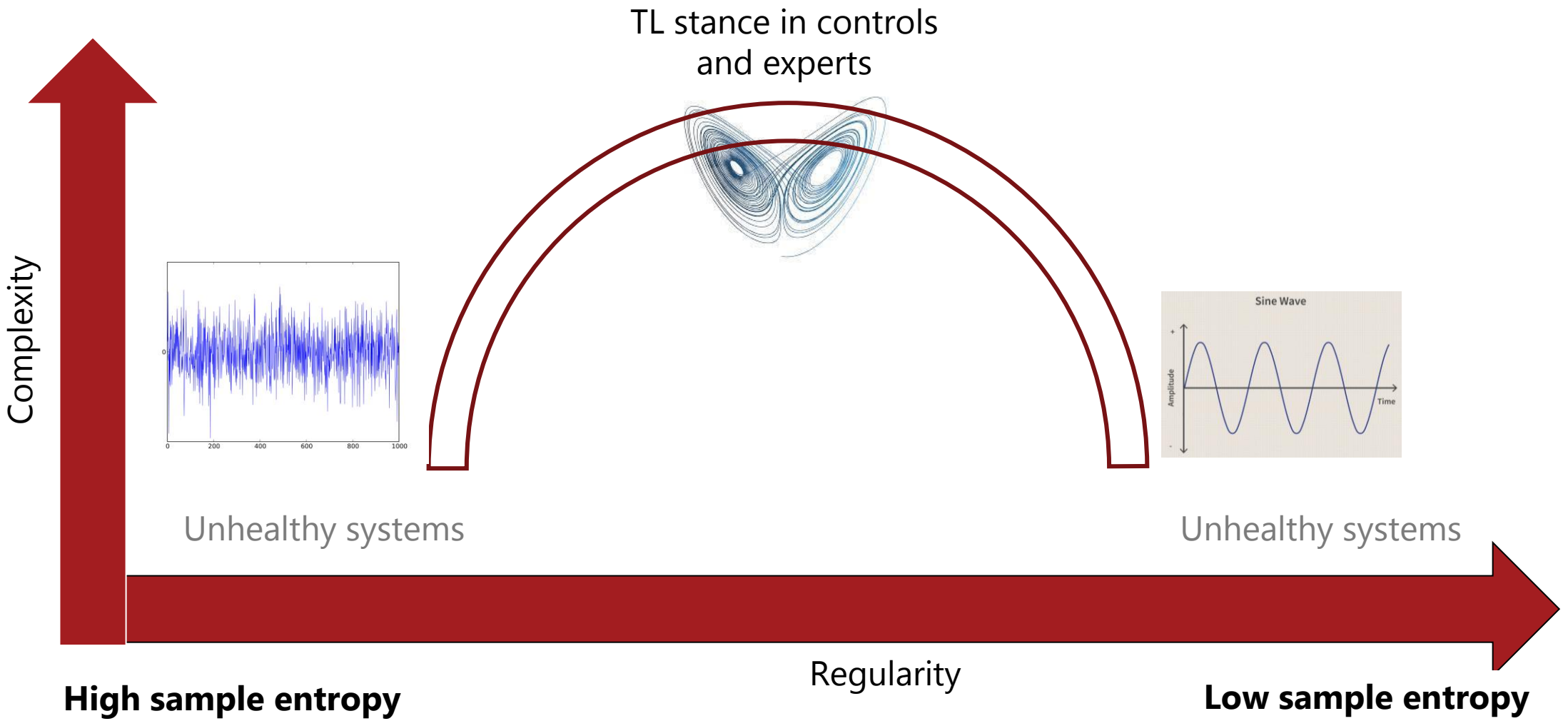
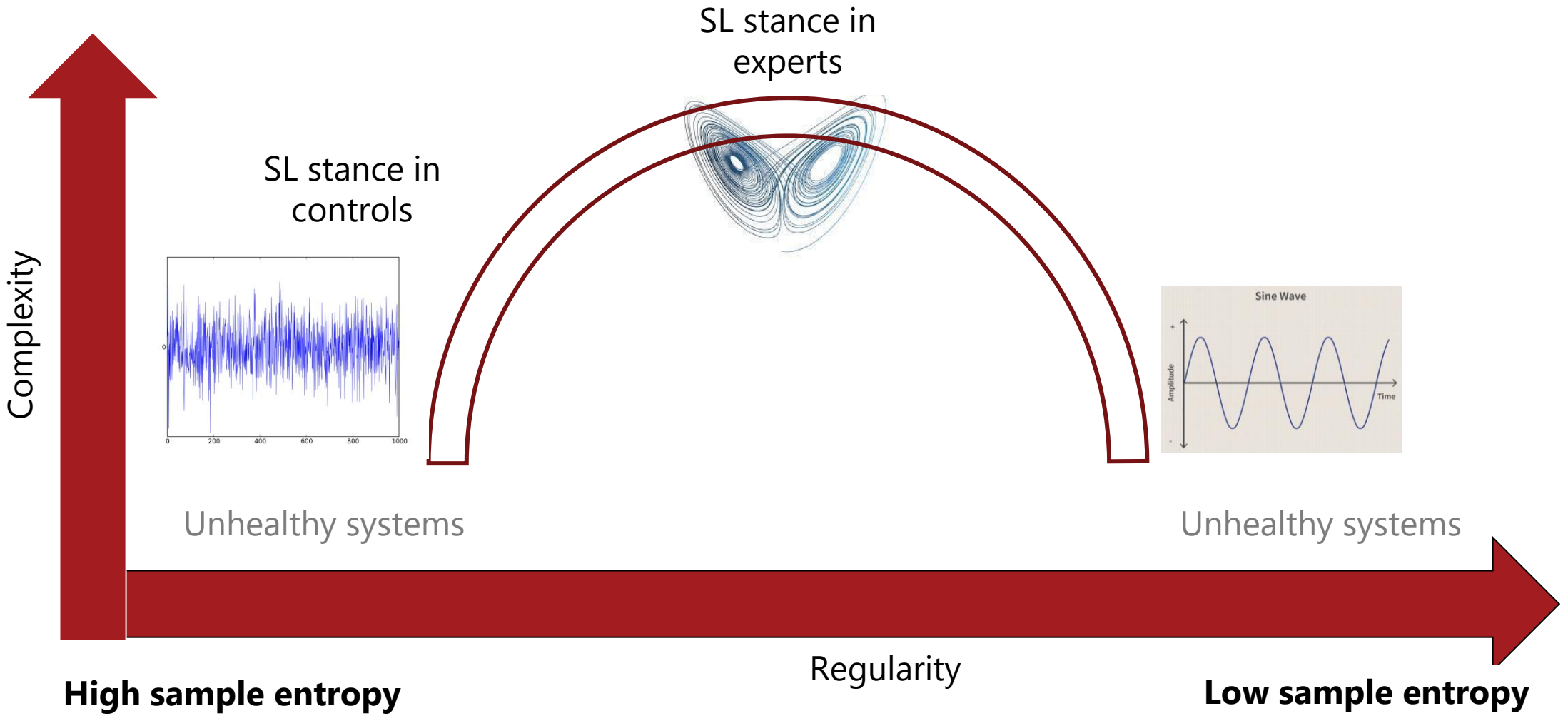
Interpretation of sample entropy in a theory



Stergiou et al. 2006

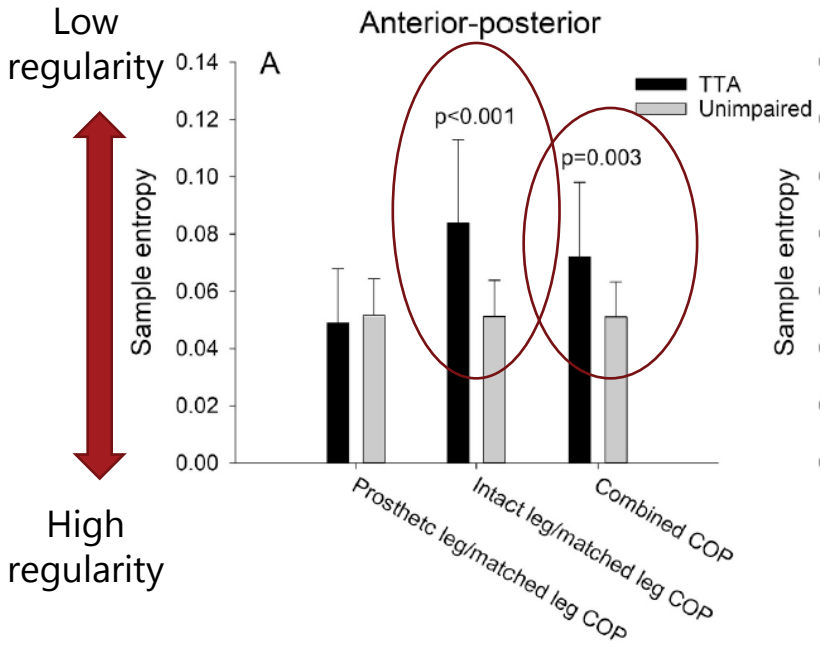
Interpretation of sample entropy in a theory



Stergiou et al. 2006

Postural control of impaired individuals

- Individuals with transtibial amputation vs unimpaired
- Upright standing on two force platforms
- Quantify regularity of the center of pressure
- TTA had less predictable movements of the combined AP center of pressure due to:
  - Less predictable movements of their intact leg
  - Not of their prosthetic leg

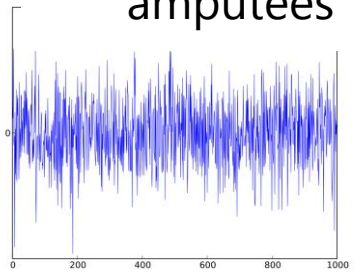


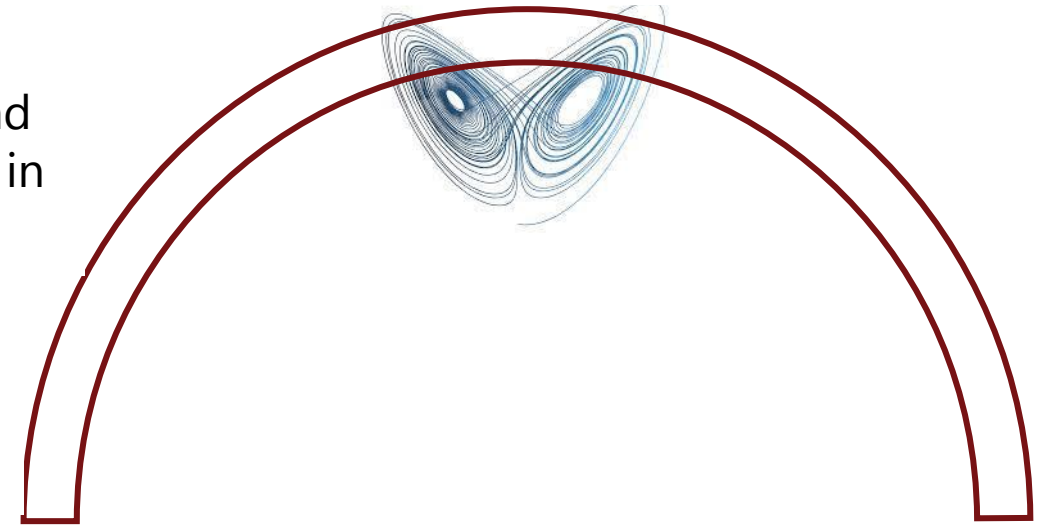
Raffalt et al. (2021)

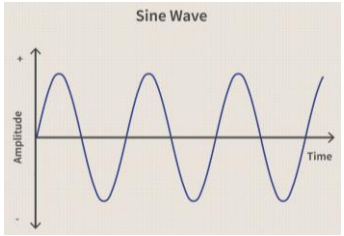
Interpretation of sample entropy in a theory

Prosthetic AP CoP

Combined and intact AP CoP in amputees







Complexity

Unhealthy systems

Unhealthy systems

Regularity

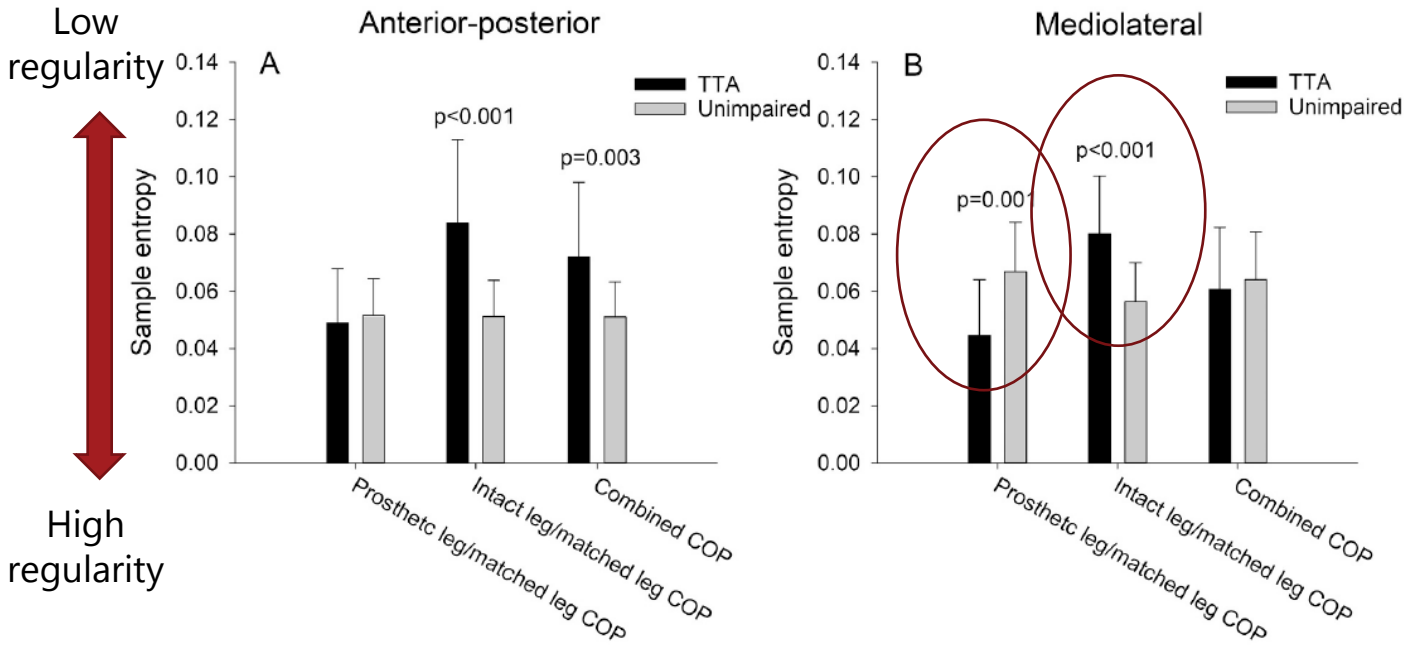
High sample entropy

Low sample entropy

Stergiou et al. 2006

Postural control of impaired individuals

- Individuals with transtibial amputation vs unimpaired
- Upright standing on two force platforms
- Quantify regularity of the center of pressure
- TTA did not differ in the predictability of the combined ML center of pressure due to:
  - Less predictable movements of their intact leg
  - More predictable movements of their prosthetic leg



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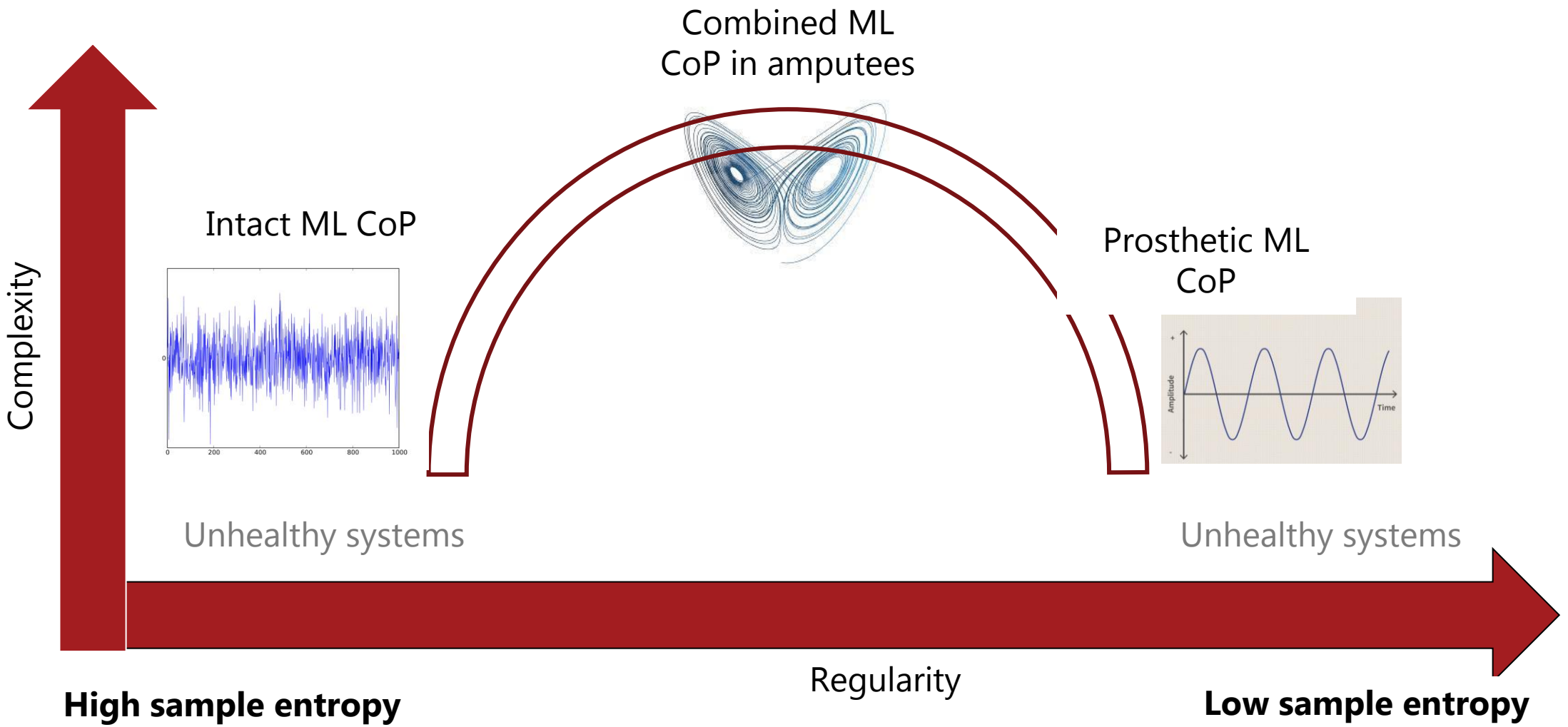


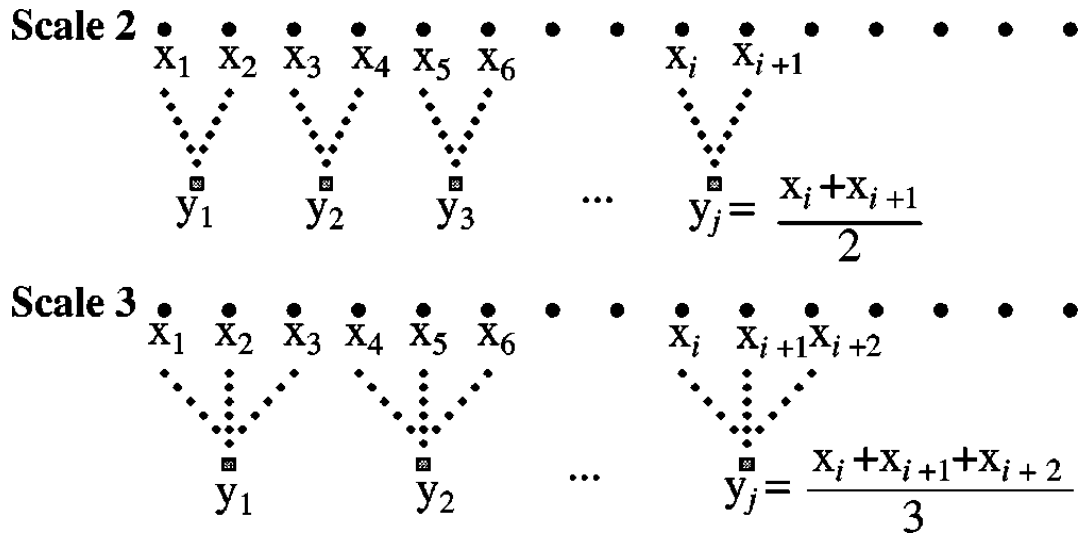
Stergiou et al. 2006

Multiscale entropy

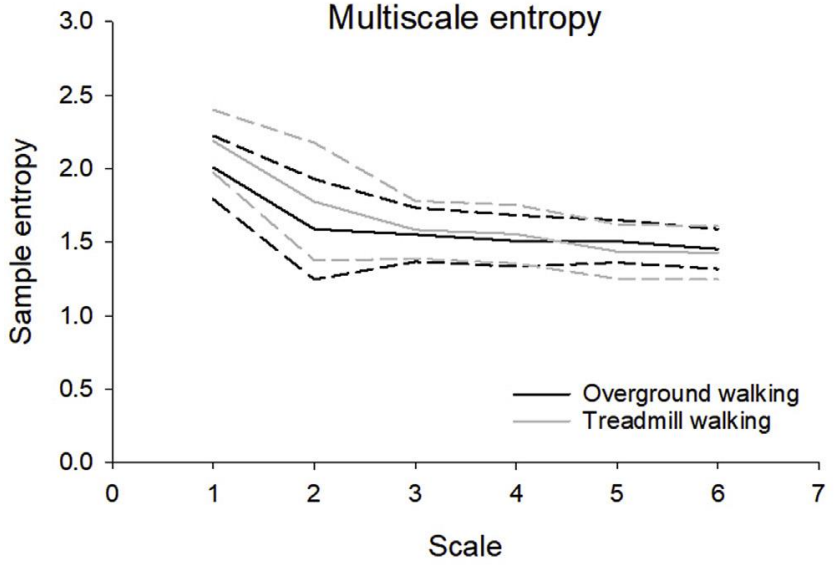
- Multiscale entropy (MSE) was introduced by Costa et al. (2002) as a measure of complexity in physiological time series.
- MSE creates multiple new time series from the one single time series recorded from the biological system in question.
- Calculate SaEn for each new time series and the original and quantifies a complexity index across multiple scales.

Multiscale entropy

- MSE procedure:
  1. Dividing the original time series into non-overlapping windows of length τ
  2. Averaging the data points within each window, creating new time series
  3. Calculate SaEn for each new time series
  4. Calculate the area below the curve as a complexity index



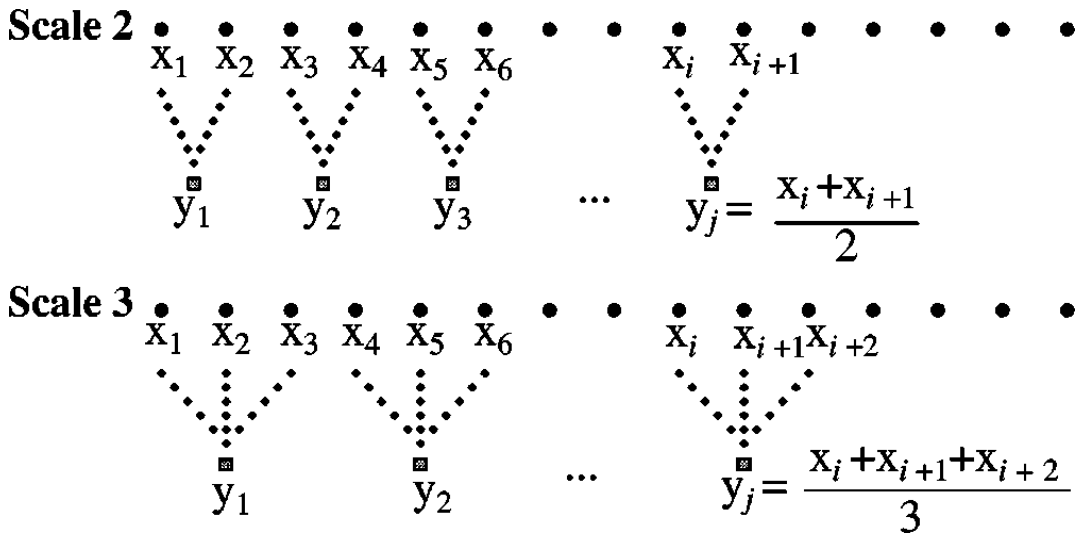
Costa et al. 2005, Adapted from Costa et al. 2002



Raffalt et al. 2018

Multiscale entropy – methodological considerations

- MSE procedure:
- Input parameters:
  - Scales
  - m
  - r
  - N



Costa et al. 2005, Adapted from Costa et al. 2002

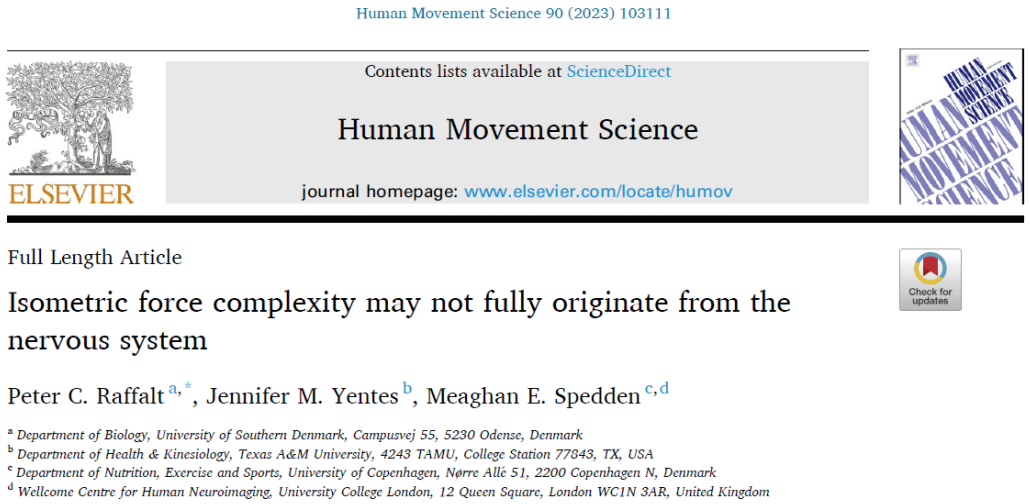
- With each rescaling the length of the new time series is reduced which could bias the SaEn calculation.

Other multiscale entropy measures

- Composite multiscale entropy
- Composite multiscale cross-sample entropy
- Refine composite multiscale entropy
- Multivariate refined composite multiscale entropy
- Multiscale fuzzy entropy
- Multiscale permutation entropy
- Generalized multiscale entropy

Multiscale entropy – example from human movement research

- Investigate the complexity of motor control of submaximal isometric contraction in children, adolescents, young adults and older adults.
- Recordings of dorsi- and plantar flexor force, soleus and tibialis anterior muscle activity and sensorimotor cortex activity.
- Quantification of complexity of each signal type using MSE.



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Full Length Article

Isometric force complexity may not fully originate from the nervous system

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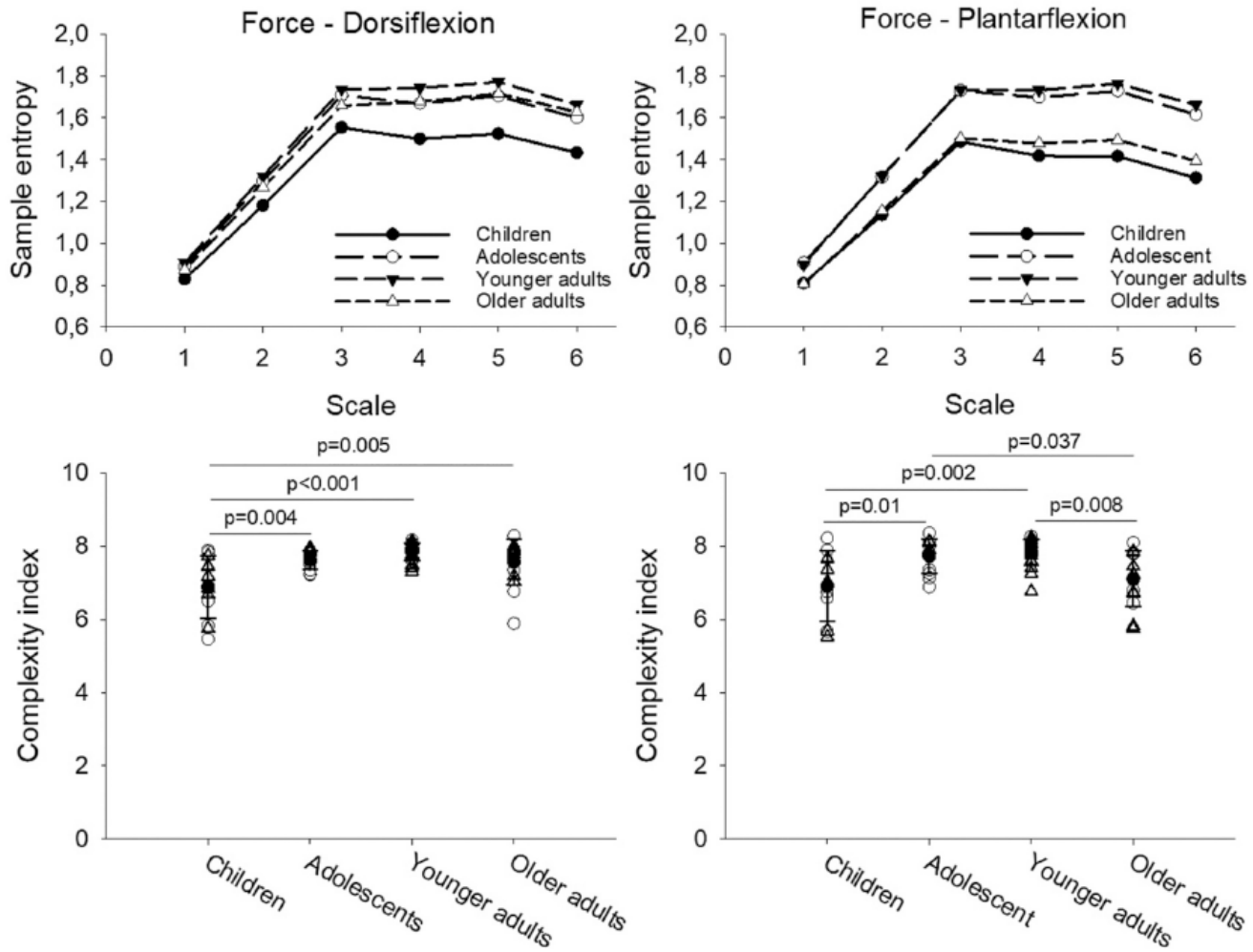
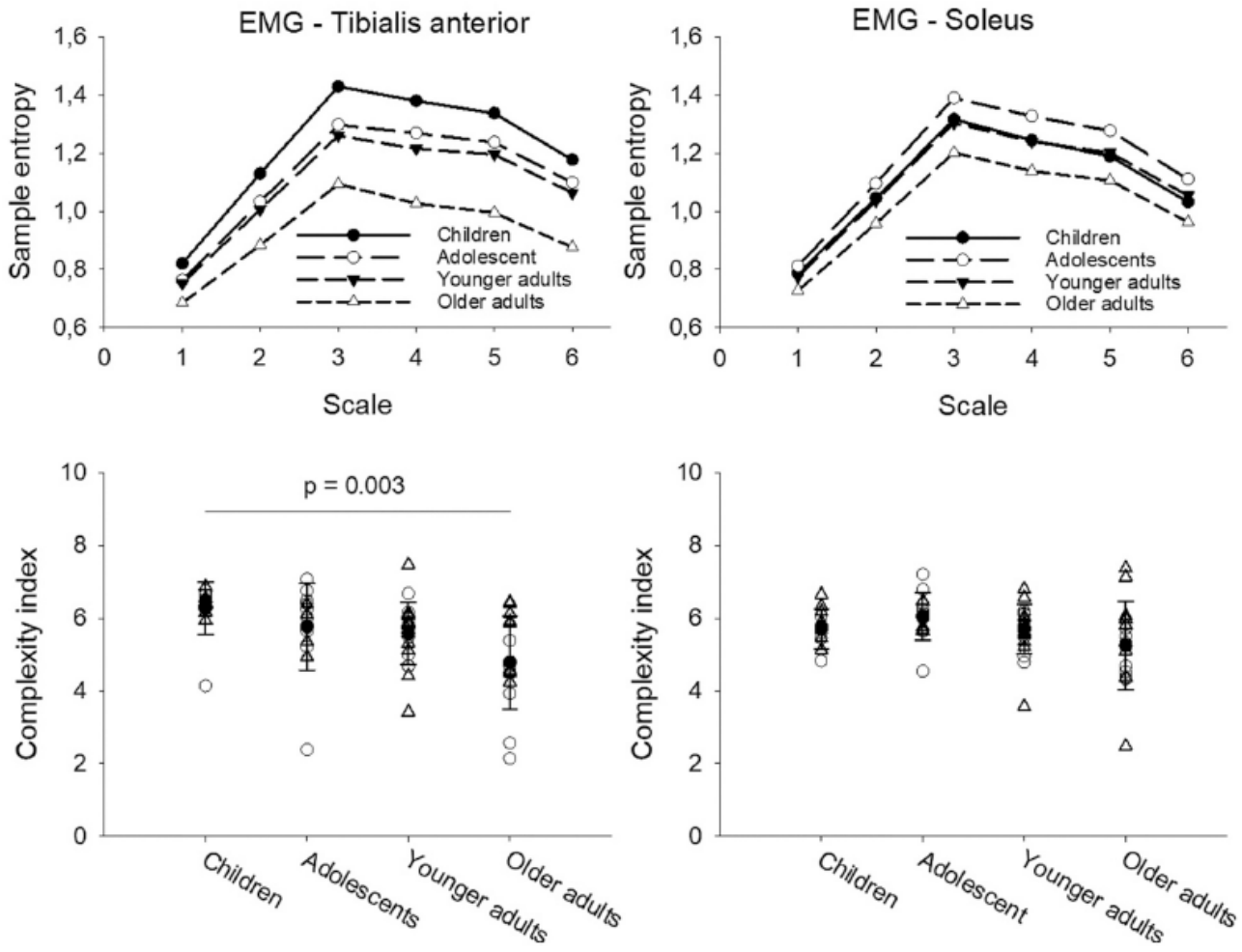
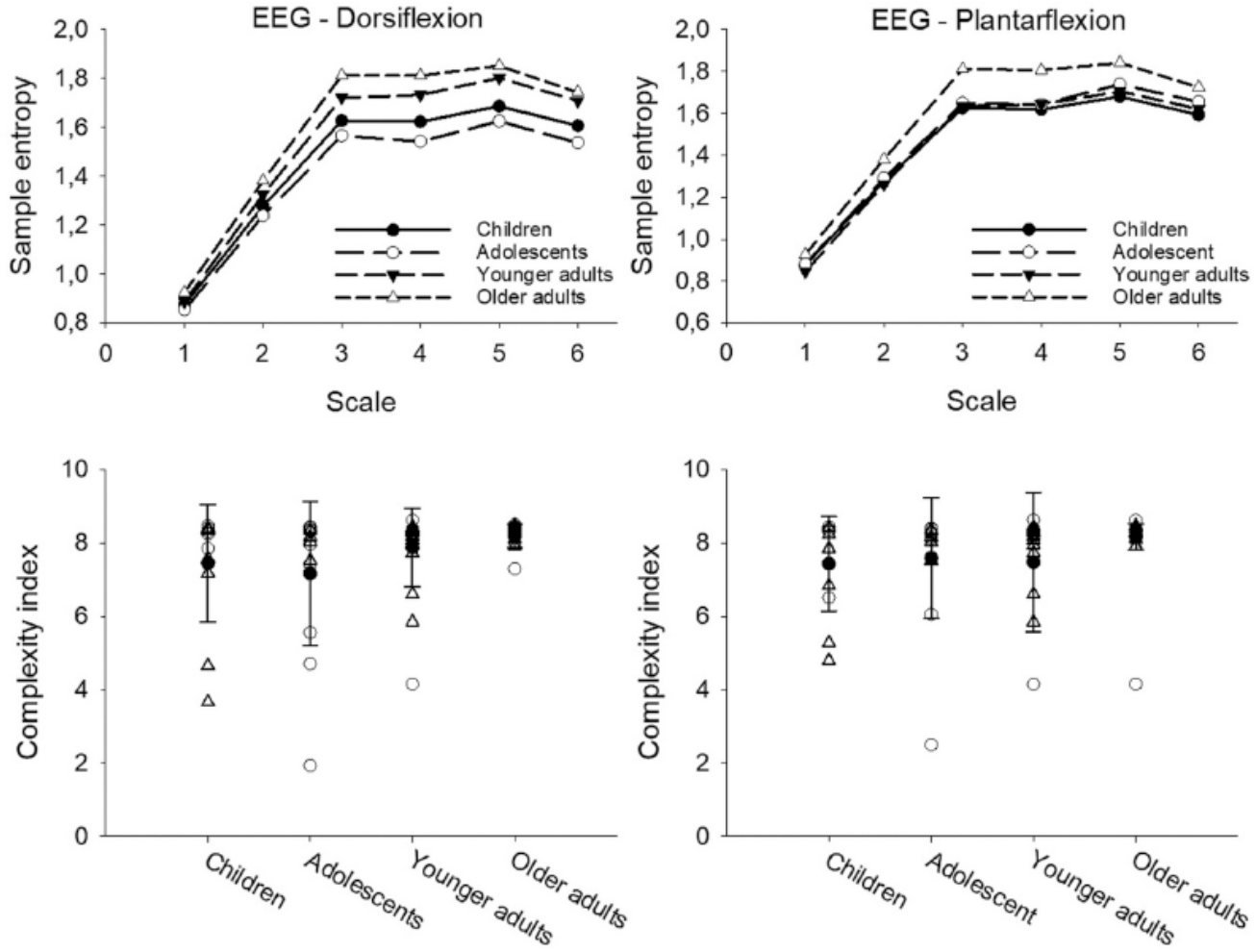
Multiscale entropy – example from human movement research



Multiscale entropy – example from human movement research



Multiscale entropy – example from human movement research



Multiscale entropy – example from human movement research

- The age-related change in isometric force complexity (inverse U-shape) was not reflected in the EMG and EEG signals.
- Suggesting that the temporal information is not transmitted unaltered between the nervous system and the musculoskeletal system.

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[d] Wellcome Centre for Human Neuroimaging, University College London, 12 Queen Square, London WC1N 3AR, United Kingdom

Take home messages

- Sample entropy quantifies regularity/predictability in a time series.

- Carefully consider:
  - Signal type
  - Sampling frequency
  - Observation time
  - Filtering

- Always check and report relative parameter consistency

- Multiscale entropy can quantify complexity/regularity across multiple time scales

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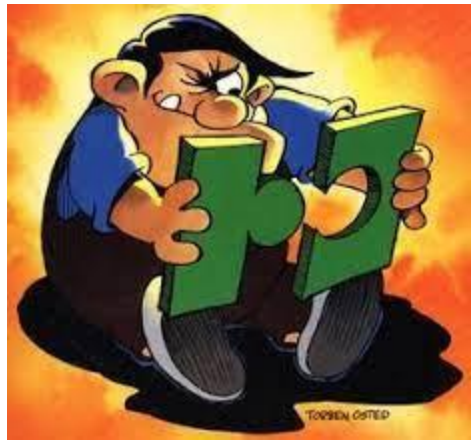
Thank you for your attention

Question?



Vir prudens non contra ventum mingit