CENTER FOR RESEARCH IN HUMAN MOVEMENT VARIABILITY

Nonlinear Analysis for the Investigation of Movement Variability: Past, Present, and Future

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AUTH Biomechanics, Aristotle University of Thessaloniki, Greece

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CURRENT STRUCTURE

- **Division of Biomechanics and Research Development (Ass. Dean and Director: Stergiou) includes**:
  1. Department of Biomechanics (Chair: Kamenskiy)
     - I. BS in Biomechanics (about 50 students)
     - II. MS in Biomechanics (about 27 students)
     - III. PhD in Biomechanics (about 25 students)
       - Department of Biomechanics has 20 tenure-track/tenured faculty and we continue to grow. Sixty percent of faculty are PIs on federal grants. Three Science covers.
       - First such academic Department in the world.
  2. Center for Research in Human Movement Variability (Director: Stergiou)
  3. Biomechanics Research Building (Director: Kaipust)

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2014: The Center for Research in Human Movement Variability is created. First with this theme in the world.

An Economic Impact evaluation of the Center since 2019 is estimated to be $27.54 million impact on the Omaha metropolitan community.

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Phase II current Research Projects

Junior Investigator	Project Title	Mentor
Dr. Nate Hunt	Variability and specificity in reactive stabilization movements to diverse slip perturbations	Dr. Al Fisher, UNMC
Dr. Philippe Malcolm	Exoskeleton optimization for reducing gait variability in patients with Peripheral Arterial Disease	Dr. Iraklis Pipinos, UNMC
Dr. Spyros Mastorakis	Use of Augmented Reality-Based Metronomes in Improving Gait in Older Adults	Dr. Nick Stergiou, UNO
Dr. Carol Curtze	Visual control of locomotion in people with Parkinson's disease	Dr. Matthew Rizzo, UNMC

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MOVCENTR Cores

- **Movement Analysis Core (Director: Dr. David Kingston)**
  - To provide biomechanical testing and support for research within the center and the community
- **Nonlinear Analysis Core (Director: Dr. Aaron Likens)**
  - **To provide analysis and interpretation of data in addition to instruction of nonlinear methods**
- **Machining and Prototyping Core (Director: Dr. Brian Knarr)**
  - To provide design, consultation, manufacturing, and prototyping services to the center and the community

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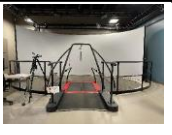

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Research Focus

- **Personal Research Focus: Human Movement Variability.**
- Variability is a fact of life. Repetition without repetition.
- The Importance of Variation In Human Movement | Dr. Nick Stergiou | TEDxUNO
- https://www.youtube.com/watch?v=0vjViLFziV4

Stergiou N. (2004). Innovative Analyses of Human Movement. Human Kinetics Publ.
Stergiou N. (2017). Nonlinear Analysis for Human Movement Variability. CRC Press.

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Previous Theories of Human Movement Variability

- For years people believed that variability is simply noise that we just want to get rid of. If we somehow can eliminate it, we will achieve perfection. We will be perfect!!! All perfect darts throwers, etc.
- It is like with the radio dial when we try to listen the beautiful crystal voice of our favorite singer.
- Is this true? Is variability simply bad for you? If yes, then why we cannot get rid of it completely?
- **"Give me a pill doc, I want to get rid of my variability!! I want to be perfect!"**

Stergiou *et al.* (2006). *J Neurol Phys Ther*, 30(3):120-129.
Harbourne & Stergiou (2009). *Phys Ther*, 89(3): 1-15.

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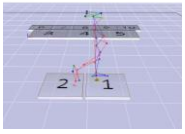
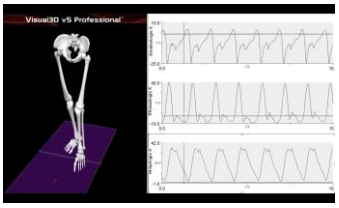
MOVEMENT UNDER THE MICROSCORE





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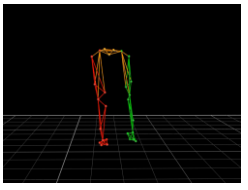

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Stergiou N. (2017). Nonlinear Analysis for Human Movement Variability. CRC Press.

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- Traditional linear tools (i.e., Standard Deviations) assume that each cycle of movement is independent of past and future cycles. Not true.
- Also assume that variations between cycles are random. Not true.
- Traditional tools give different answers when compared with nonlinear measures.

Stergiou N. (2004). Innovative Analyses of Human Movement. Human Kinetics Publ.
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- Linear Measures
  - Variability around a mean; explores few strides that do not have continuous
  - Answers: How much movement?
  - **AMOUNT or MAGNITUDE**
- Nonlinear Measures
  - Variability of the pattern; explores how the movement evolves over time, multiple continuous strides.
  - Answers: What type of movement?
  - **TEMPORAL STRUCTURE or ORGANIZATION**

Sosnoff et al. (2006). *Neurosci Lett.* 392(3):165.
Stergiou *et al.* (2006). *J Neurol Phys Ther*, 30(3):120-129.

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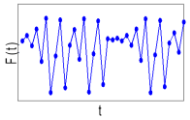
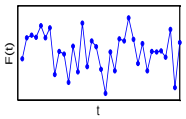
Dimension 1

Data 1



Mean = 0.59
SD = 0.30

Data 2



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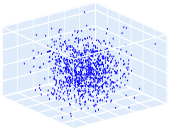
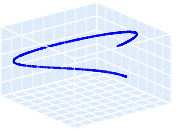
Dimension 3

Data 1



Data 2



- Data 1 is generated by a random mechanism.
- Data 2 is generated by a deterministic mechanism.

Stergiou N. (2004). Innovative Analyses of Human Movement. Human Kinetics Publ.
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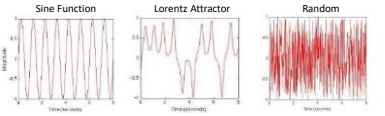

Periodic Chaotic Unpredictable

Approximate/Sample Entropy	~0	0.1	1.5
Correlation Dimension	0.3	1.9	5.1

Stergiou N. (2004). Innovative Analyses of Human Movement. Human Kinetics Publ.
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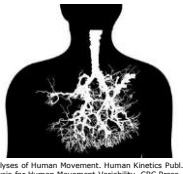
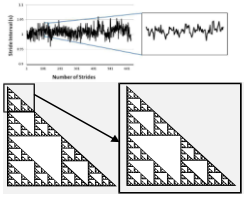
VARIABILITY IS NOT NOISE BUT HAS PATTERNS

There are a few big, many medium size, and a huge number of small size fluctuations even in most fundamental movement such as walking. Pink noise type of a process (or a distribution) with a frequency spectrum such that the power spectral density is inversely proportional to the signal's frequency. Such patterns are everywhere.





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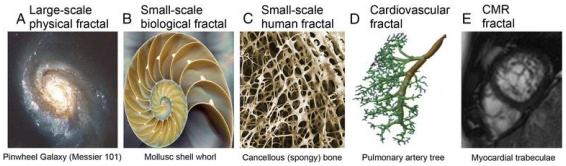

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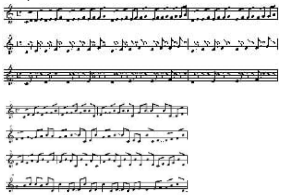
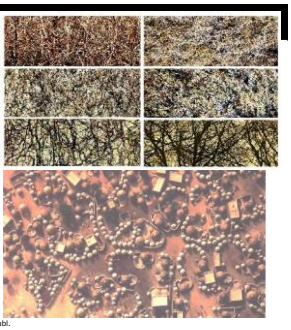
WE ALSO LIKE SUCH PATTERNS

A work of art is pleasing if it is neither too regular and predictable nor pack too many surprises.





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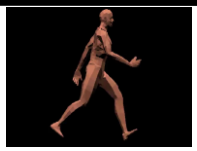
The Theory

- PATHOLOGY AFFECTS THESE HEALTHY PATTERNS.
- On one end, we could be rigid as we see in orthopedics where you may behave like a robot due to an injury
- Or at the other end, we could be very noisy like a **frail older adult**



Stergiou *et al* (2006). *J Neurol Phys Ther*, 30(3):120-129.
Stergiou & Decker (2011). *Human Mov Sci*, 30(5):869-88

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The Theory

- HEALTH IS A RICH BEHAVIORAL STATE
- … complex but with beautiful patterns
- "Life is an aperiodic crystal, it is not random, but also is not periodic, it is something in between…" by Erwin Schrodinger: What is Life" (1944)
- Variability may be the spice of life!!!

Stergiou *et al* (2006). *J Neurol Phys Ther*, 30(3):120-129.
Stergiou & Decker (2011). *Human Mov Sci*, 30(5):869-88

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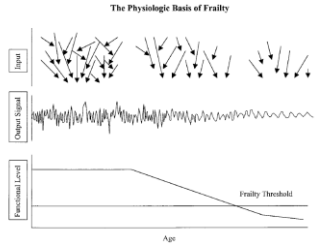
The Theory

Loss of Complexity Hypothesis



Lipsitz LA (2002). Journal of Gerontology: BIOLOGICAL SCIENCES

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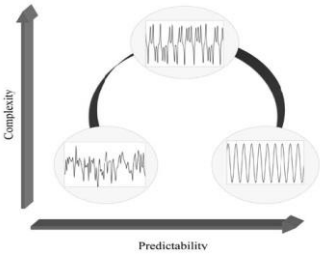
The Theory



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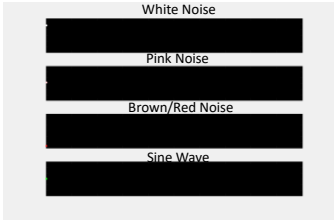
Important Definitions

Temporal Persistence: when looking at a time series the temporal correlation refers to how different points are related to each other.



- ⟵ No Correlation – Random
- ⟵ Moderate Correlation – Healthy
- ⟵ Strong Correlation – Rigid
- ⟵ Very Strong Correlation – Very Rigid

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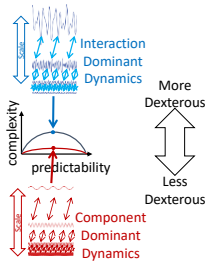
The Theory

Theory of Complex Adaptive Behavior (our theoretical model as evolved in 2015 & 2017).

- **More dexterous behavior is associated with fractally nested scales of activity supported by non-linear couplings of components both within and across scales.**
- **As a fundamental feature of human movement, multifractality opens new avenues for conceptualizing the link between physiologic interactivity and adaptive capacity.**



Harrison & Stergiou (2015). *Nonlinear Dynamics Psychol Life Sci, Oct;19(4):345-94.*
Cavanaugh, Kelly-Stephen, Stergiou. (2017). J Neurol Phys Ther. Oct;41(4):245-251.

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THE "NEXT STEP"

- It is now well documented that complexity in healthy movement such as gait and posture (along with variability in other, healthy biological signals e.g., heart rate), and a loss of this complexity in sports injury, as well as in a variety of neurodegenerative and physiological disorders, could lead to rigidity or randomness (Stergiou, Goldberger, Lipsitz, Costa, Hausdorff, Rhea, Delignieres, Newell, West, and many others).
- Now we need the innovative "next step" that goes beyond these descriptive studies that characterize levels of variability in various populations.

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THE "NEXT STEP"

- Can we **restore** healthy levels of complexity? Can we design devices to enhance complexity? What kind of devices?
- When we have healthy complexity are we **more adaptable**? Are we **more economic**? Are we **more dexterous**? Are we more capable of learning new tasks? Are we better in terms of our **navigation capabilities**?

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THE "NEXT STEP"

- What are the **reasons** that we have this complexity? How different biorhythms **interact**?
- What are the **optimal thresholds** that can allow a more sensitive and reliable application of these metrics for understanding human physiology?
- Eventually this research should aim to devise novel interventions and technologies that will harness biological variability and create new possibilities for those in need to improve performance and/or restore their decreased physical abilities.

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STRONG INFERENCE

1) Devising alternative hypotheses;
2) Devising a **crucial** experiment (or several of them), with alternative possible outcomes, each of which will, as nearly as possible, exclude one or more of the hypotheses;
3) Carrying out the experiment to get a clean result;
1') Recycling the procedure, making sub-hypotheses or sequential hypotheses to refine the possibilities that remain

Note: CRUCIAL experiment means that you really test what you seek to test

Platt S. Science 1964. *et al*.

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DEVELOPMENT OF COMPLEXITY

Stergiou *et al* (2013). *Kinesiology Review*, 2:93 – 102

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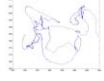
DEVELOPMENT OF COMPLEXITY

- Center of Pressure (COP) is the point of application of the ground reaction force
- COP is comprised of two time series
  - COPx (Anterior-Posterior)
  - COPy (Medial-Lateral)

Medial-lateral

COPy



COPx

Anterior-posterior

- SWAY VARIABILITY can be measured separately in each direction

Harbourne & Stergiou (2003) Develop. Psychobiol., 42(4):368-377.
Stergiou et al. (2006) J. Neurol. Phys. Ther., 30(3):120-129.

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Step #1: Do we have sufficient reliability regarding the measures of sway variability for assessing the development of sitting postural control? YES

- We tested intra-session and inter-session reliability of linear and nonlinear tools.
  - **Typically developing infants**
  - **Infants with or at risk of Cerebral Palsy**
- The nonlinear tools presented high intra-session and inter-session ICC values.
- The evaluation of Center of Pressure data is a reliable method of investigating the development of sitting postural control. Reliability improved as sitting skill matured.

Kyvelidou et al. (2009). Arch. Phys. Med. Rehab., 90, 1176-1184
Kyvelidou et al. (2010). Arch. Phys. Med. Rehab., 91, 1593-1601

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Step #2: Do nonlinear and linear variables describe different features of sway variability? YES

- Linear measures are positively correlated with other linear measures. Non-linear measures are positively correlated with other non-linear measures. Linear measures are negatively correlated with non-linear measures.
- Linear measures increase during development of sitting while nonlinear measures decrease (less noisy) in the AP direction. The exact opposite in the ML direction showing an interesting de-coupling.
- Linear and Nonlinear measures load on different factors using a PCA.

Deffeyes et al (2009). Clin. Biomech., 24:564-570; Harbourne et al (2009). Nonlinear Dyn. Psych. Life. Sc., 13(1):123-44; Cignetti et al (2010). Gait Posture, 33(1):88-92

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Step #3: Can measures of sway variability discriminate between typically developing infants and infants with developmental delay? YES

- Nonlinear measures provide information about small improvements in postural control over time that were not apparent with standard clinical tests such as the Gross Motor Function Measure.
- Nonlinear measures revealed significant differences between infants with typical versus delayed development.
- The infants with delayed development were found to have more rigid and less complex patterns of postural sway as compared to typically developing infants (also in gait and in supine posture).

Deffeyes et al (2009). J. Neuroeng. Rehabil., 6(1):34; Deffeyes et al (2009). Clin. Biomech., 24:564-570; Deffeyes et al (2009). Nonlinear Dyn. Psychol. Life Sci., 13(4):351-68

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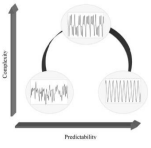
Step #4: Can we translate our complexity model to design therapies to improve sitting postural control for infants with motor developmental delay? YES



Optimal Movement Variability: healthy functioning

COMPLEXITY PROBLEMS	BEHAVIORAL EXPRESSION	POSSIBLE INTERVENTIONS
OVERALL REDUCED COMPLEXITY	Very little active movement	Increase Sensory Information – NATURE based Physical Guidance
INCREASED RANDOMNESS UNPREDICTABILITY	Constant pushing and pulling into extreme ranges	Provide soft constraints to suggest reduced range
INCREASED PREDICTABILITY RIGIDITY	Static posture; rigid, stiff, hypotonic	Environmental adaptation to encourage slight active movement out of preferred posture

Harbourne & Stergiou (2009). Phys. Ther., 89, 267-282.

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- The infants with motor disabilities
- Infants are randomly assigned to either receive a home program or twice weekly perceptual-motor PT intervention
- Both home program and direct intervention are 8-week programs; either 8 home visits or 16 direct PT sessions
- Data collection in lab pre-intervention, at halfway point, immediately post intervention, and 1 month post intervention
- The infants are either diagnosed or they are at risk for cerebral palsy (5 months - 2 years)

Harbourne et al., (2010). Phys. Ther., 90(12), 1-18

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PRE THERAPY

POST THERAPY

Harbourne et al., (2010). Phys. Ther., 90(12), 1-18

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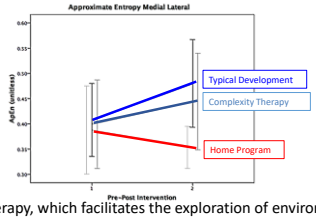

Perceptual motor therapy, which facilitates the exploration of environment through nature-based paradigms, enhances the complexity of sitting postural control and assembles the developmental trend of infants with typical development.

Harbourne et al., (2010). Phys. Ther., 90(12), 1-18

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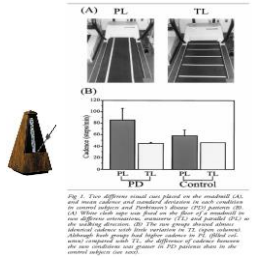
Restore?



- VISUAL and AUDIO METRONOMES
- In Controls variability disappears with a periodic signal from a metronome. They walk like robots!
- Parkinson's disease patients "benefited" from a metronome in a similar fashion.
- During metronomically paced walking, long-range correlations disappear.
- **NO long term effects.**

Hanakawa et al. (1999) Ann Neurol 45:327-336
Hausdorff et al. (1996) J Appl Physiol 80(5):1448-57

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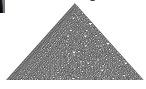
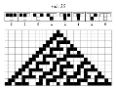
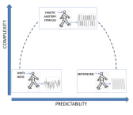
The Crucial Experiment

How could you create such an auditory signal?

The chaotic/fractal music was created from the WolframTones website (http://tones.wolfram.com) using Rule 30 as it is a class III rule that generates chaos which is found in nature.







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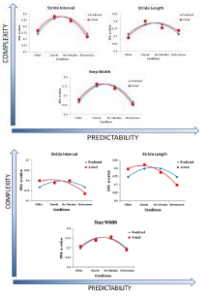
Restore?

Older Adults

Young Adults



Kaipust et al. Ann Biomed Eng. 2013 Aug;41(8):1595-603.

40

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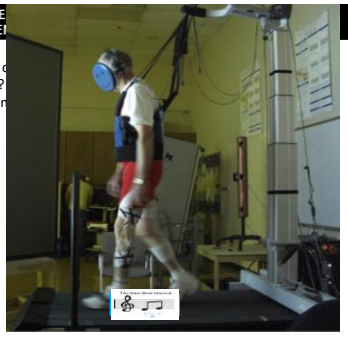
HUMAN MOVE

How could you c
auditory signal?
translated into r



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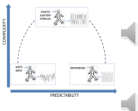
Restore?



Red Noise (representing low complexity, high predictability, rigidity)

Pink Noise (representing high complexity)

White Noise (representing low complexity, low predictability, rigidity)

Hunt et al (2014). Sci Rep. Aug 1;4:5879.

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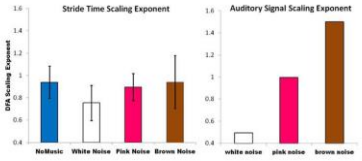
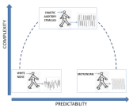
Restore?





Young Adults

Hunt et al (2014). Sci Rep. Aug 1;4:5879.

43

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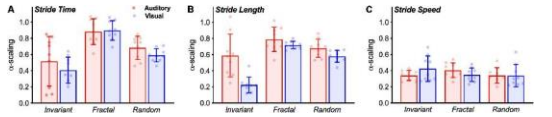
Restore?

AUDITORY vs VISUAL STIMULI



Vaz et al. (2020). Front Physiol 11:67

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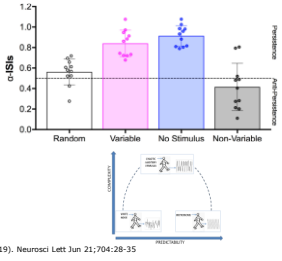
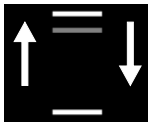
Restore?

Healthy Young Overground with VISUAL STIMULI



Stimulus Display



Glasses

Vaz et al. (2019). Neurosci Lett Jun 21;704:28-35

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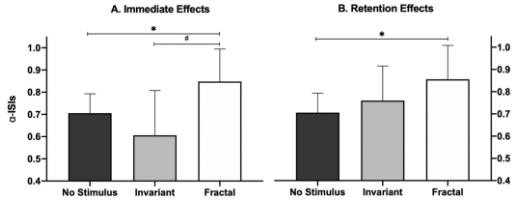
Restore? Retention?

Older Adults Overground with VISUAL STIMULI (Acute Restoration)

Older adults walked 8 min with i) no stimulus (self-paced), ii) a variable fractal-like visual stimulus and iii) an invariant visual stimulus. In the two visual stimuli conditions, the participants walked 8 additional minutes after the stimulus was turned off.



Vaz et al. (2020). Hum Mov Sci Dec;74:102677

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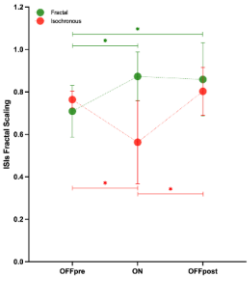
Restore? Retention?

Fig. 1 Inter-stride intervals fractal scaling (α-ISIs) for both isochronous (ISO) and fractal (FRC) before (OFFpre), during (ON) and after (OFFpost) cued walking.



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STRONG INFERENCE

- CRUCIAL experiment means that you really test what you seek to test
- Ducharme et al (2018) Hum Mov Sci, 58:248-249
- "This relationship, known as fractal dynamics, is thought to represent the adaptive capacity of the locomotor system. However, this has not been tested empirically. Thus, the purpose of this study was to determine if stride time fractality during steady state walking associated with the ability of individuals to adapt their gait patterns when locomotor speed and symmetry are altered. Fifteen healthy adults walked on a split-belt treadmill at preferred speed, half of preferred speed, and with one leg at preferred speed and the other at half speed (2:1 ratio asymmetric walking). The asymmetric belt speed condition induced gait asymmetries that required adaptation of locomotor patterns. The slow speed manipulation was chosen in order to determine the impact of gait speed on stride time fractal dynamics."
- "These findings suggest there [illegible] be a relationship between unperturbed preferred or slow speed walking fractal dynamics and g[illegible]ptability."

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Adaptable?

- The 1/f stimulus group exhibited a faster recovery time after perturbation compared to the periodic stimulus group, with a difference in median recovery time of 3.3 seconds ($p = 0.021$). There was no difference between the two groups for self-selected walking speed ($p = 0.889$), implying that walking speed did not influence the study outcome.

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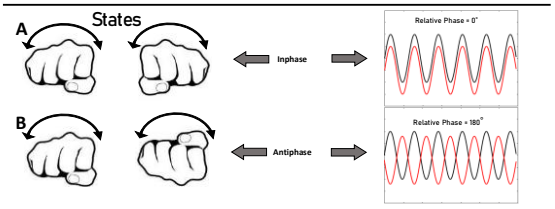
Adaptable?

Does a pink noise stimulus affect our upper-limb coordination?



S. Kelso, 1997.

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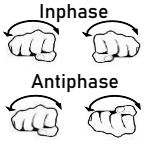
Equipment Setup | Initial Movement Pattern | Metronome Type



Pink Noise
White Noise
Brown Noise
Isochronous Signal

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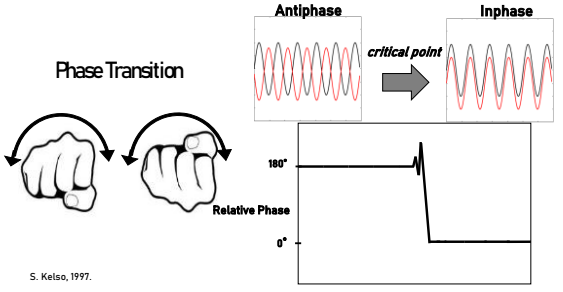
Adaptable?



S. Kelso, 1997.

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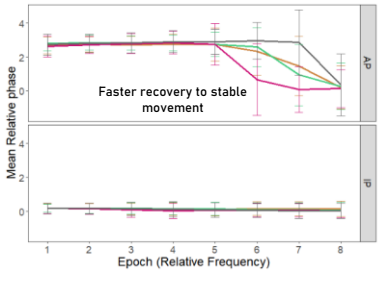
Adaptable?



Coordination, when exhibiting a pink noise variability structure, exhibits a behavior that adapts significantly faster to a more stable behavioral state

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STRONG INFERENCE

- CRUCIAL experiment means that you really test what you seek to test
- Rock et al (2018) J Exp Biol, Nov 12;221(Pt 22):jeb181834.
- "Here, we aimed to determine the interaction between metabolic cost of transport and step length variability during human walking at different speeds. In particular, two aspects of step length variability were analyzed: the amount of variations ('variations') and the organization of the step-to-step fluctuations ('fluctuations'). Ten healthy, young participants walked on a treadmill at five speeds, ranging from 0.75 to 1.75 m s^{-1}."
- "No effect of speed was observed on fluctuations (P=0.342)."
- "Fluctuations have little [illegible] effect on metabolic cost of transport, but still may relate to preferred walking speed."

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More Economic?

- 21 healthy subjects from University of Nebraska at Omaha volunteered to participate
- 12-minutes self-paced baseline trial used to find average and standard deviation for each subject
- Subjects then walked in three randomized pacing conditions: Pink-Gaussian, White-Gaussian, Isochronous
- All stimulus conditions lasted for 12 minutes

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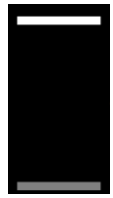
More economic?

Methods



- Visual pacing signal created in Unity (left)
- VuFine mini HDMI glasses (top right)
- Noraxon FSR SmartLead footswitches (middle right)
- Wearable Metabolic System (bottom right)

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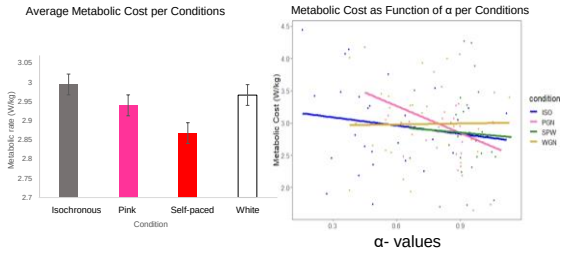
Yes, more economic!!!



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Interact?

Patients with a lower limb amputation have increased stride-to-stride fluctuations for their prosthetic limb compared to their non-amputated limb, as well as compared to individuals without amputation.

Is there a connection between patient perception/reported outcomes and stride-to-stride fluctuations?

- 13 unilateral transtibial amputees walked on treadmill at a self-selected pace for 3 minutes
- **2 conditions:** Walking trial in prescribed prosthesis and alternate prosthesis
- Prostheses properly aligned by certified prosthetists
- Subjects recorded degree of preference on continuous visual analog scale
- Change in LyE measured and correlated with preference

Wurdeman *et al. J Rehab Res,* 2013.
Wurdeman *et al. Ann Biomed Eng*, 2013.

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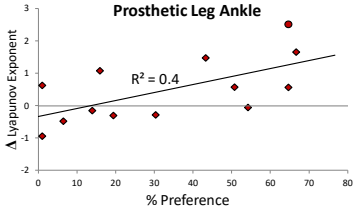
Interact?



Wurdeman *et al. J Rehab Res,* 2013.
Wurdeman *et al. Ann Biomed Eng*, 2013.

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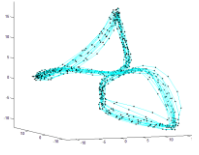
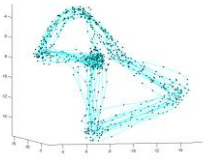
Interact?



Which one is the preferred attractor?



Wurdeman et al. (2013) *JRRD.* 50(5):671-86.

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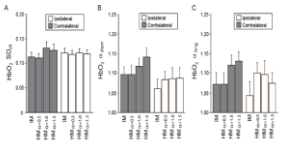
- Manipulated changes of the exponent α of the experimental stimuli produced corresponding changes in the exponent α of both tap-to-tap intervals and cortical hemodynamics.
- The changes in hemodynamics were in both motor and sensorimotor cortical areas in the contralateral hemisphere.
- **Complex auditory stimuli engage both brain and behavior at the level of variability scaling structures.**



Harrison et al. Neuroscience. 2018 Jun 26. pii: S0306-4522(18)30436-6.

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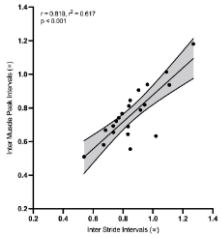
Fig. 1 The correlation between Inter Muscle Activity Intervals (α-IMPIs) and Inter Stride Intervals (α-ISIs). The individual data points represent each participant value.



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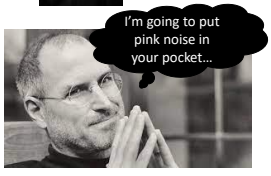
Nonlinear Analysis Core as an app developer



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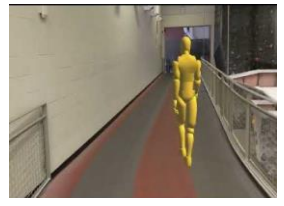
- Avatar-based metronomes for gait training
- Can we implement such avatar-based metronomes with AR?

Figure: The Microsoft Hololens 2 AR headset



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The optimal thresholds for using DFA might allow a more sensitive and reliable application of this metric for understanding human walking physiology than has been achieved to date.

A meta-analysis = a mean scaling exponent α threshold of 0.86 [2 standard error (0.76, 0.96)] is able to optimally discriminate temporal organization of stride interval between young and old, whereas 0.82 (0.72, 0.92) differentiates patients with PD and age-matched asymptomatic controls.

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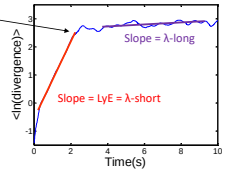
Misconceptions…

λ-short & λ-long

- Bruijn et al. *Med Eng Phys. 2012 May;34(4):428-36* "Our findings support the use of λ-short, but not λ-long, as a measure of human gait stability."

The separation of the two trajectories cannot grow further apart than the boundary of the attractor, and therefore, there are plateau regions in the plot.



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Many more on going projects with these great people on restoration, circadian rhythms, probability distribution and temporal patterns in visual cueing/stimuli, etc.

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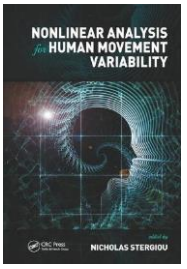
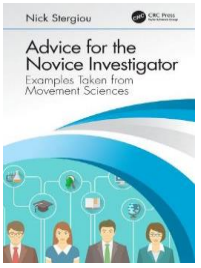
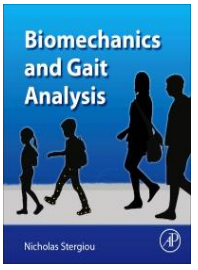
IF YOU WANT TO READ MORE ABOUT MANY OF THE DIFFERENT TOPICS OF TODAY'S TALK READ MY RECENT BOOKS







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THANK YOU!!!!!

All my students and collaborators all over the world.
My funding sources (National Institutes of Health, the US Depart. of Education, NASA, NSF, VA, the Nebraska Research Initiative, and many others).

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