EFFECT OF FATIGUE ON DYNAMICAL MODEL OF THE CROSS COUNTRY CYCLE

F. Cignetti, A.H. Rouard, F. Schena

University of Savoy, France

University of Rovereto, Italy

Diagonal stride?

Involves arms and legs working in right-left pairings

Diagonal stride versus classical gaits ?

testing	Cycle velocity (m/s)	Cycle length (m)	Cycle frequency(Hz)	references
Diagonal stride, flat				
15km	**4.7-4.92**	**5.38-5.92**	**0.81-0.87**	Komi et al (1982) Norman&Komi (85-87)
3km	**4.22**			Bilodeau et al (91)
slow	**3.1-4.47**	**5.08-7.9**	**0.57-0.70**	Gagnon(81), Nilsson (2004),Roy&Barbeau(90)
middle	**3.8-5.38**	**5.7-7.14**	**0.7-0.75**	Gagnon (81) Nilsson (2004)
fast	**4.75-5**	**5.95-6.1**	**0.8-0.81**	Bilodeau(92)Nilsson (2004)Roy (90)
max	**5.64-6.79**	**5.9-7.9**	**0.9-1**	Gagnon (81)karvonene (89) Nilsson(2004)
Walking, flat				
Slow to fast	**1.45-2.5**	**1.5-2**	**0.92-1.3**	Murray (67) Hay (2003)
Running, flat				
Slow to fast	**2-9.2**	**1.4-4.6**	**1.35-2.6**	Luthanen (78) Williams(85)

Diagonal stride versus classical gaits ?

Joints angles	Diagonal stride (4.8-6m/s)	Running (3-6m/s)	Walking (1.5-2.2m/s)
hip	60-85°	60-75°	40-48°
knee	20-30°	90-103°	55-65°
references	Gagnon (1981) Komi et al (1982)	Milliron &Cavanagh(1990) Nilsson et al (1985)	Murray (1967) Perry (1992)

Diagonal stride gait differs from classical gaits (i.e. walking and running) for equivalent cycle velocities:

- **longer cycle lengths**
- **shorter cycle frequencies**
- **shorter range of motion of the knee.**

because of a gliding phenomenon and use of poles and skis

Fatigue in cross country ?

- **Decrease of cycle velocity with decrease of cycle length**
- **Decrease of the maximal isometric force developed by the extensors of the knee less in cross country then in running**
- **Peripheral fatigue**

(Viitassalo et al., 1982 ; Bilodeau et al., 1996; Millet et coll. 2003; Zory et al, 2006)

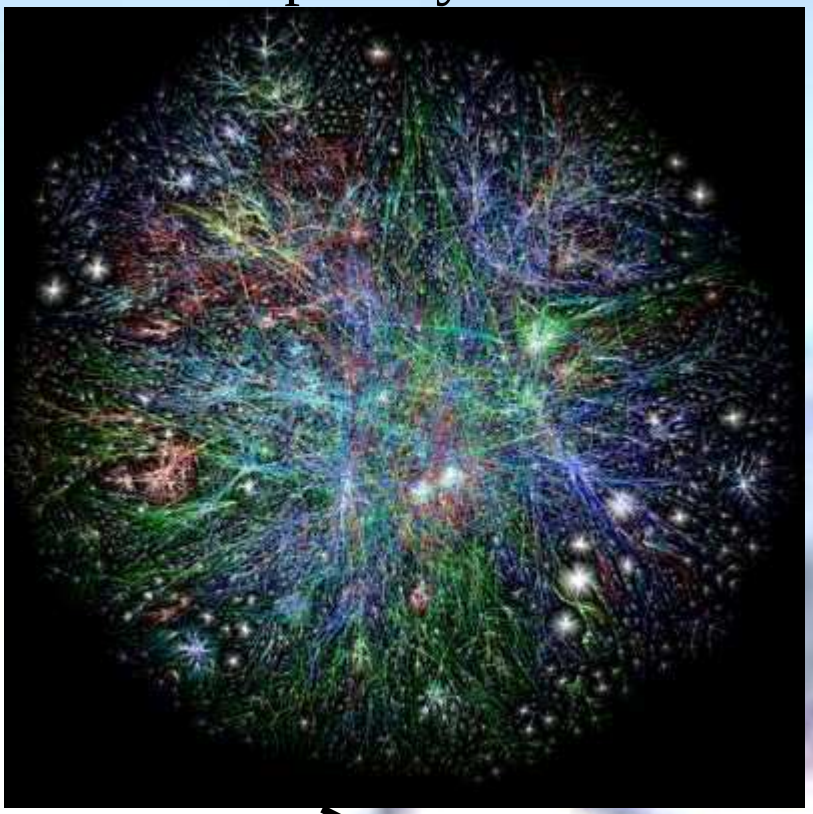
The fatigue induce modifications of some gait parameters.
No information about their impacts on the organization and coordination of the movements.

What are the effects of fatigue on the skier behavior :

- **On the parameters of the dynamical model ?**
- **On the amplitude and the nature of the movement variability?**

Dynamical system theory ?

Complex system



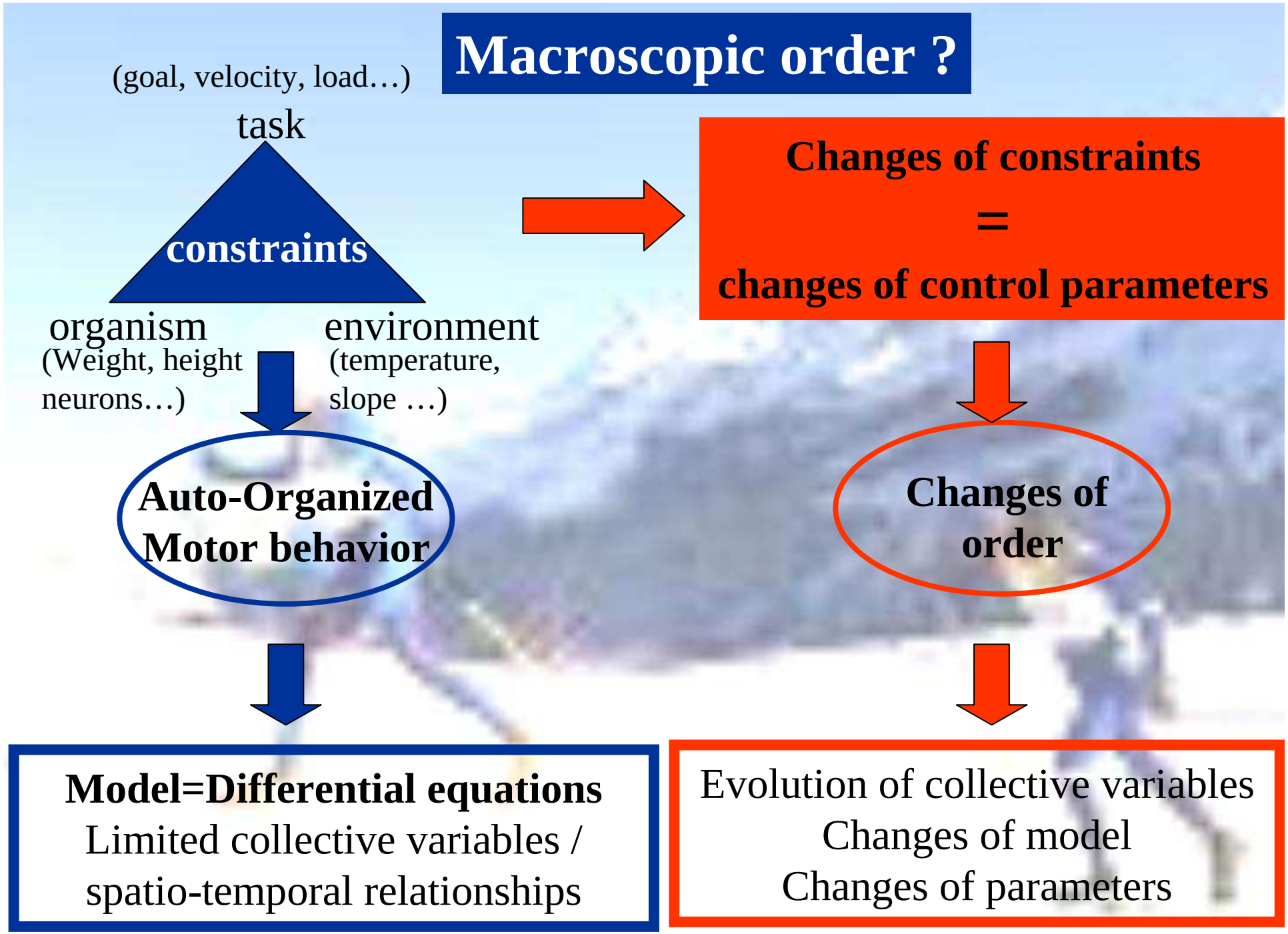
Neuromuscular system

$N \approx 10^2$

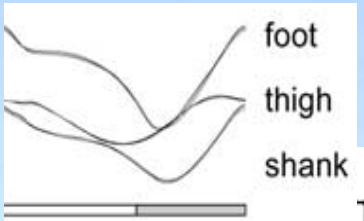
$N \approx 10^3$

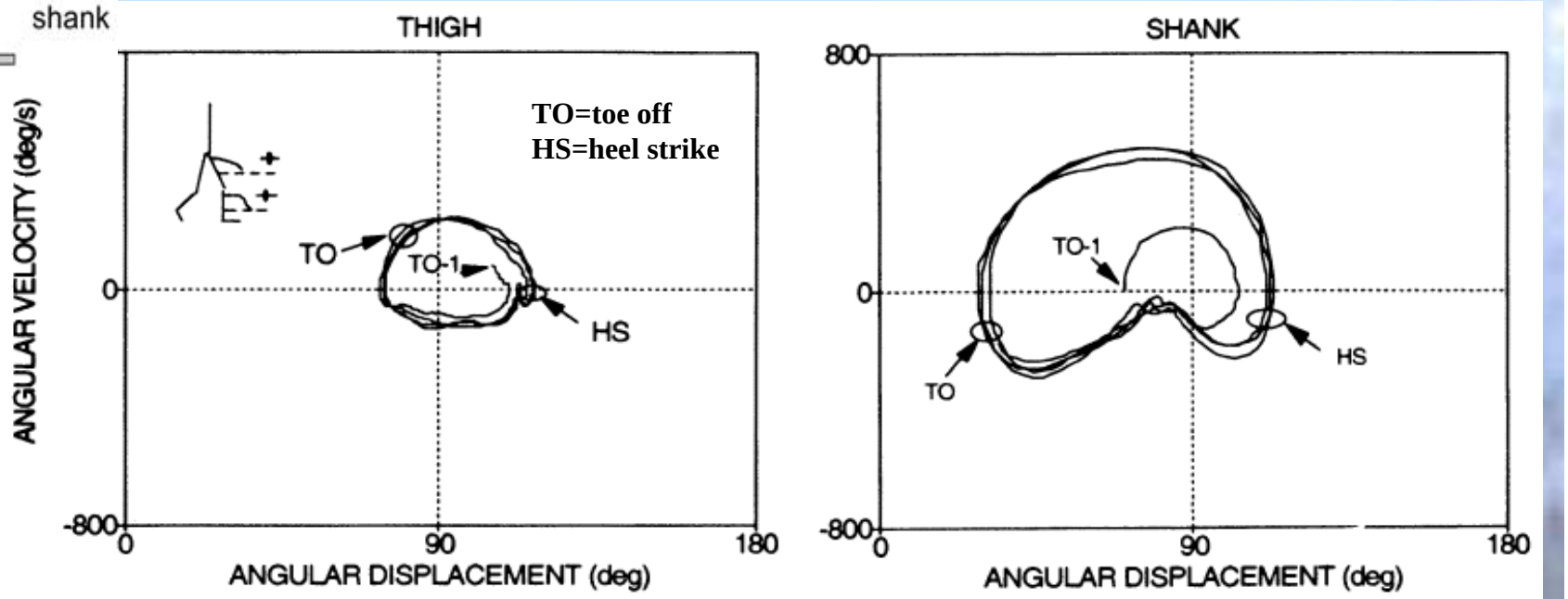
$N \approx 10^{14}$

Interaction
Coordination
=>
Macroscopic order


Macroscopic order ?
(goal, velocity, load…)
task
constraints
organism
(Weight, height
neurons…)
environment
(temperature,
slope …)
Changes of constraints
=
changes of control parameters
Auto-Organized
Motor behavior
Changes of
order
Model=Differential equations
Limited collective variables /
spatio-temporal relationships
Evolution of collective variables
Changes of model
Changes of parameters

Example of human gait



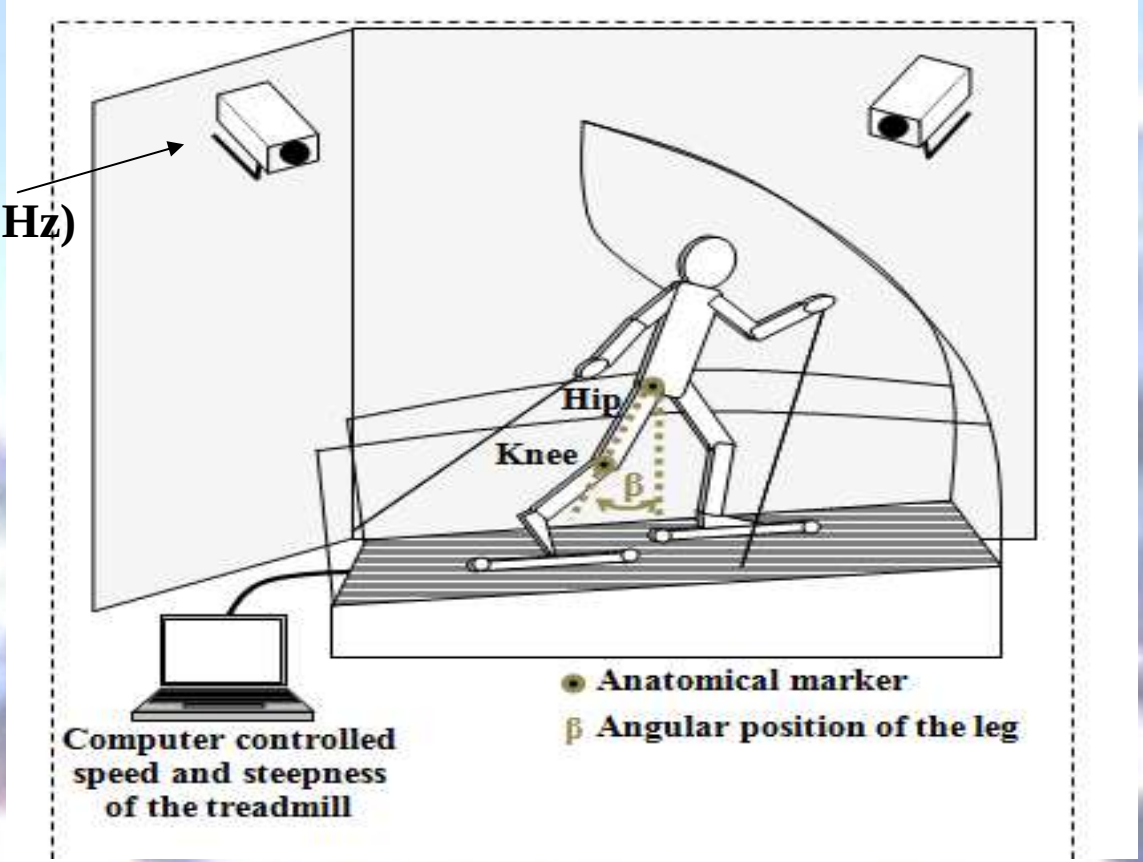


Collective variables: angular velocity- angular displacement
=>Phases space
⇒Organization = same kind of cyclic attractor less perfect for shank
(even thigh and shank trajectories differed, Clark & Philipps, 1993)
= stable state

What happen with fatigue (organismic contraint,control parameter)?
What happen in cross country skiing (different constraints)?

Methods

6*Pro reflex MCU (100Hz)

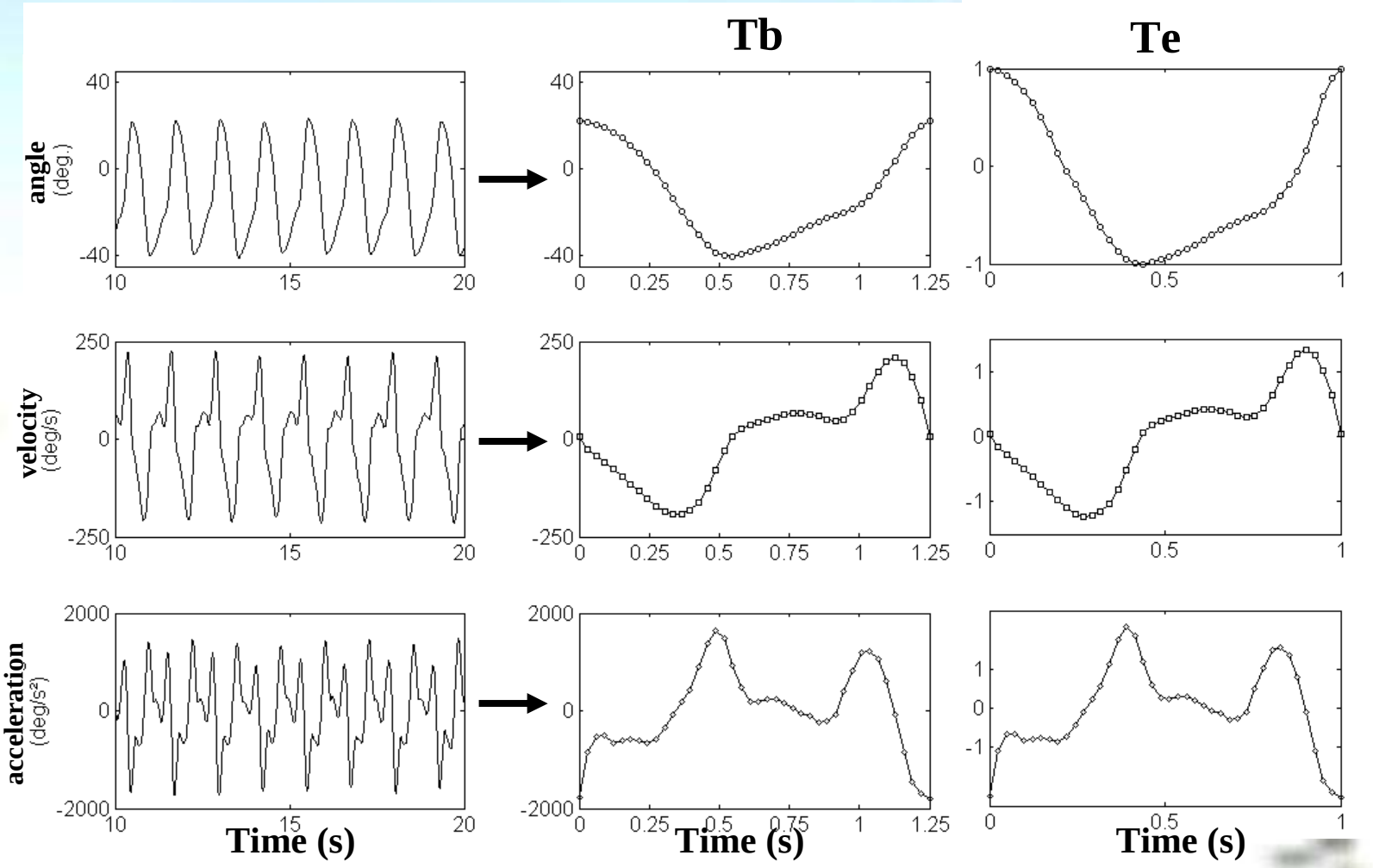


- 4♀/4♂ (age:18 years ± 2.58; height:1.70 m ± 0.11; body weight:60.75 kg ± 10.28)
- up to exhaustion at constant speed-steepness corresponding to 90% VO^2max
- Kinematics data recorded during 40s at the beginning (Tb) and end of the test (Te)

Kinematics treatment

- The kinematics data (i.e., angular position, velocity and acceleration) of the leg were summarized in an average normalized cycle for Tb and Te.

[Mottet & Bootsma, 1999]



Type of Model

1-The leg motion was then modeled as second-order dynamics with a fixed origin, mass and main frequency, of the kind: (Beek et al., 1995)

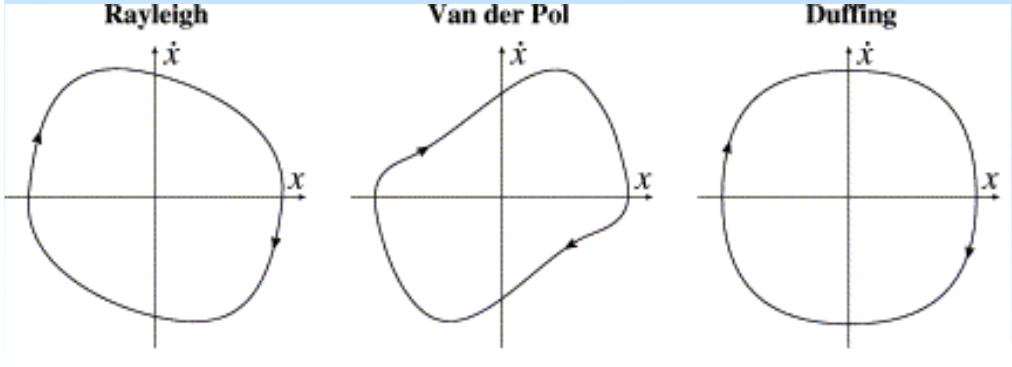
$$\ddot{x} + F(x,\dot{x}) = 0$$

where x was the spatial deviation from the origin, the dot represented differentiation with respect to the time, and the F function summarized the linear stiffness plus the contribution of all the nonlinear (stiffness and damping) components of the motion.

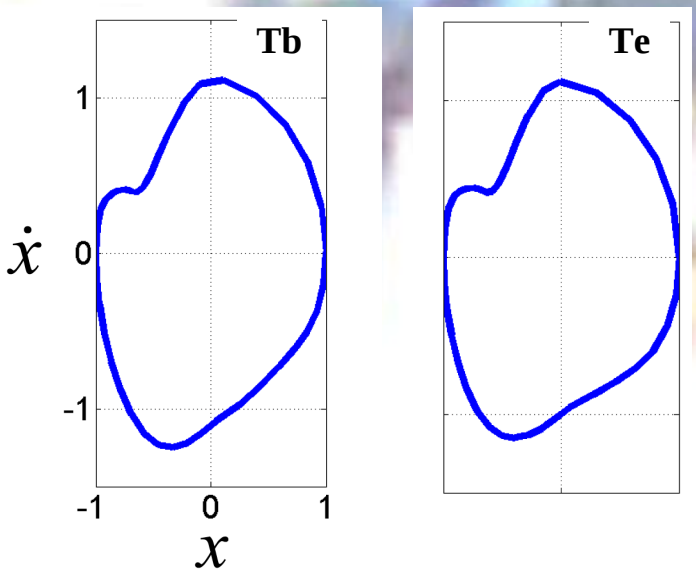
2-Qualitative graphical analyses were done to identify the stiffness and damping components underlying the rhythmic leg movements and quantitative statistical procedures to assess their respective contributions

3-Differences in the model between Tb and Te were assessed using repeated-measures analyses of variance (ANOVA).

Qualitative Results 1



Phase plane representation was used to determine the damping function.

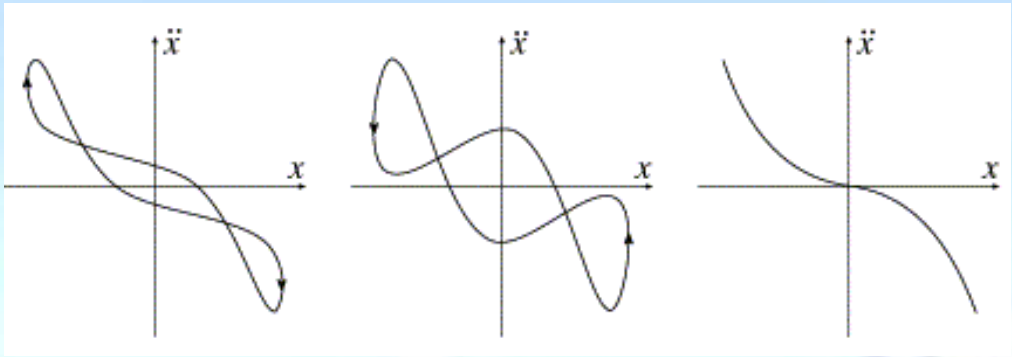


- **For Tb and Te,the phase planes denoted a Van der Pol-type damping.**

$$\ddot{x} + x - \dot{x} + x^2\dot{x} = 0$$

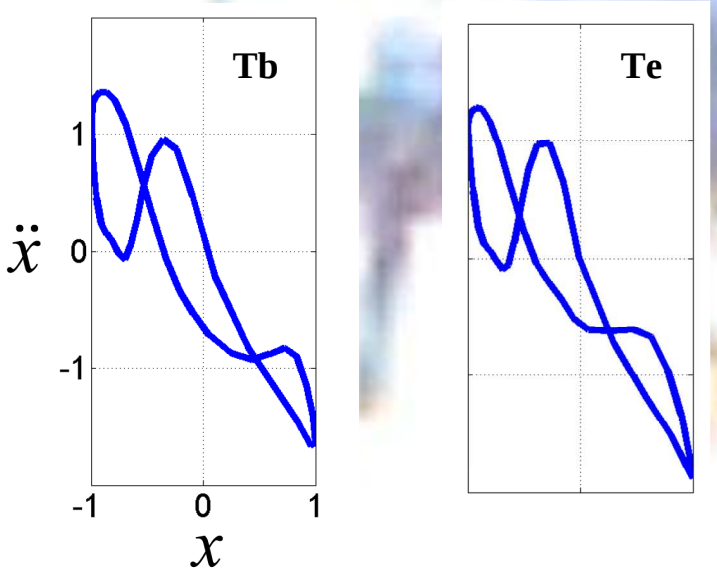
Van der Pol damping

Qualitative Results 2



Hooke's plane representation was used to assess the stiffness function.

A linear (harmonic) oscillator is characterised by a straight line in Hooke's plane,



- For Tb and Te, the Hooke planes did not reveal clearly the presence of non-linear stiffness terms in the kinematic data

$$\ddot{x} + \underbrace{x}_{\text{Linear stiffness}} = 0$$

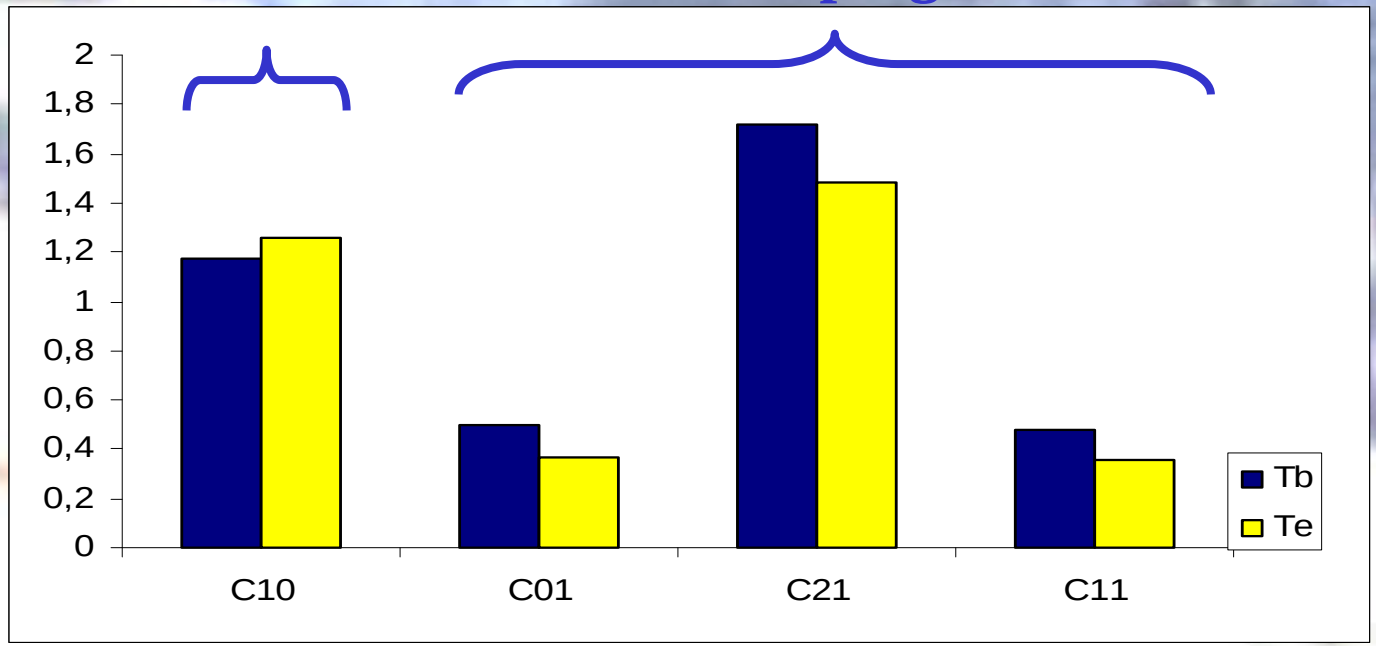
Influence of fatigue on the model

Qualitative results 1+2 =>
model must include stiffness and damping functions

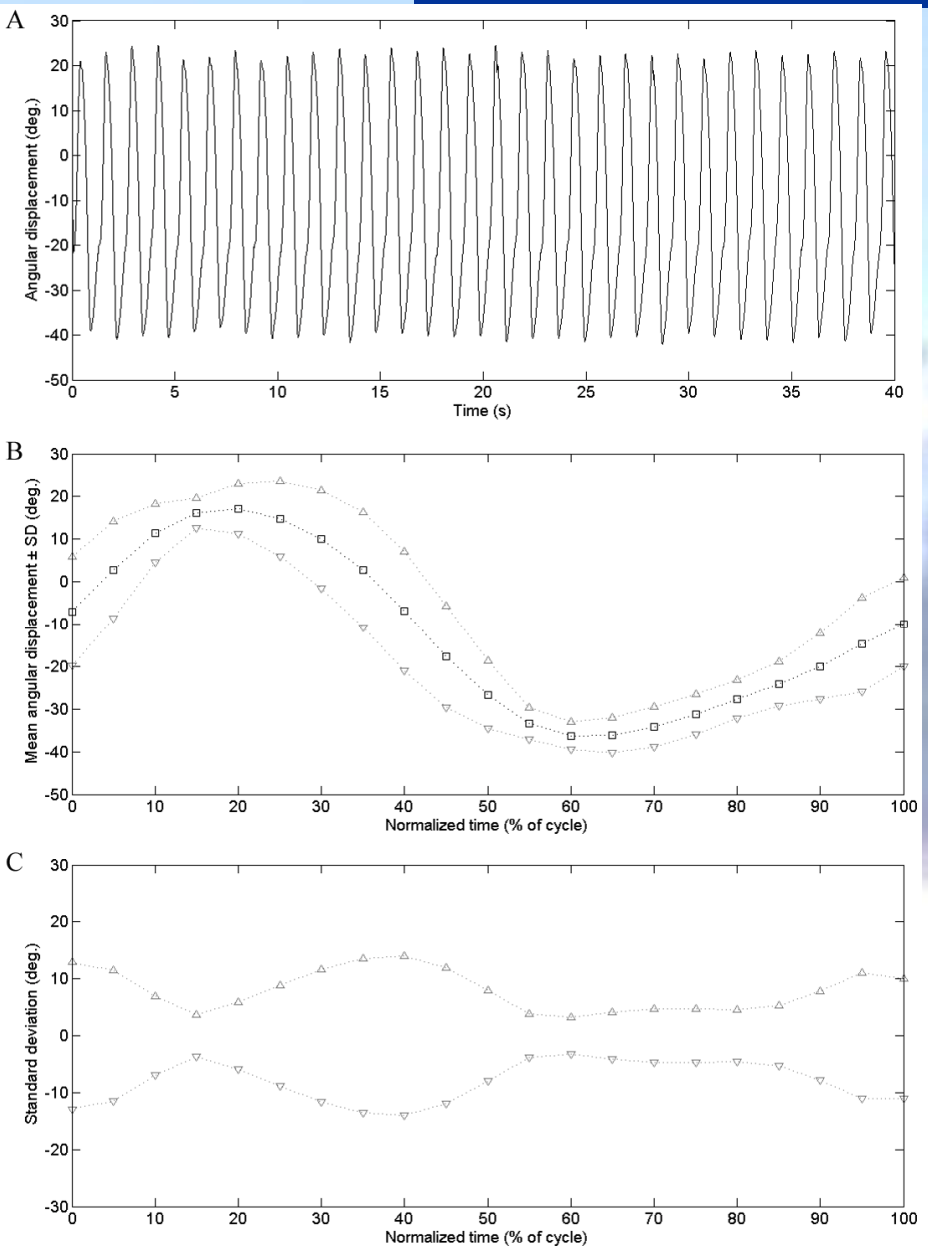
With fatigue model remained unchanged

$$\ddot{x} + c_{10}\,x - c_{01}\,\dot{x} + c_{21}\,x^{2}\,\dot{x} - c_{11}\,x\dot{x} = 0$$

but **stiffness** ↗ **damping** ↘



Method to evaluate the variability



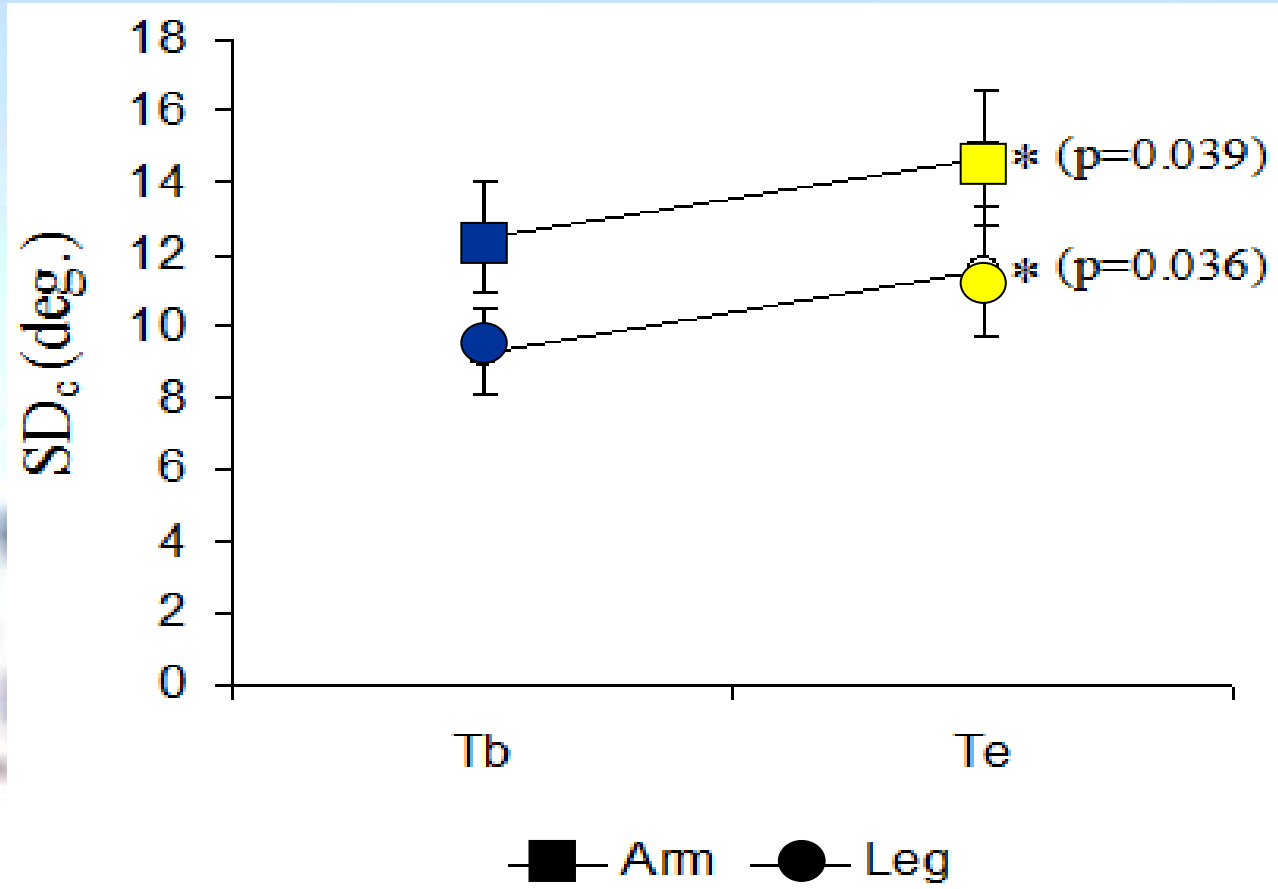
- To quantify the magnitude of variability in the time series, the angular displacements of the limbs for each movement cycle were time normalized each 5% between 0 and 100%.

- Standard deviations across all cycles were calculated for each 5% normalized time and averaged over the normalized cycle to produce a single measure of mean variability (***SDc***)

$$SD_c = \langle SD_i(x) \rangle \text{ for } i \in \{0\%,\ldots,100\%\}$$

Both for Tb and Te

Results

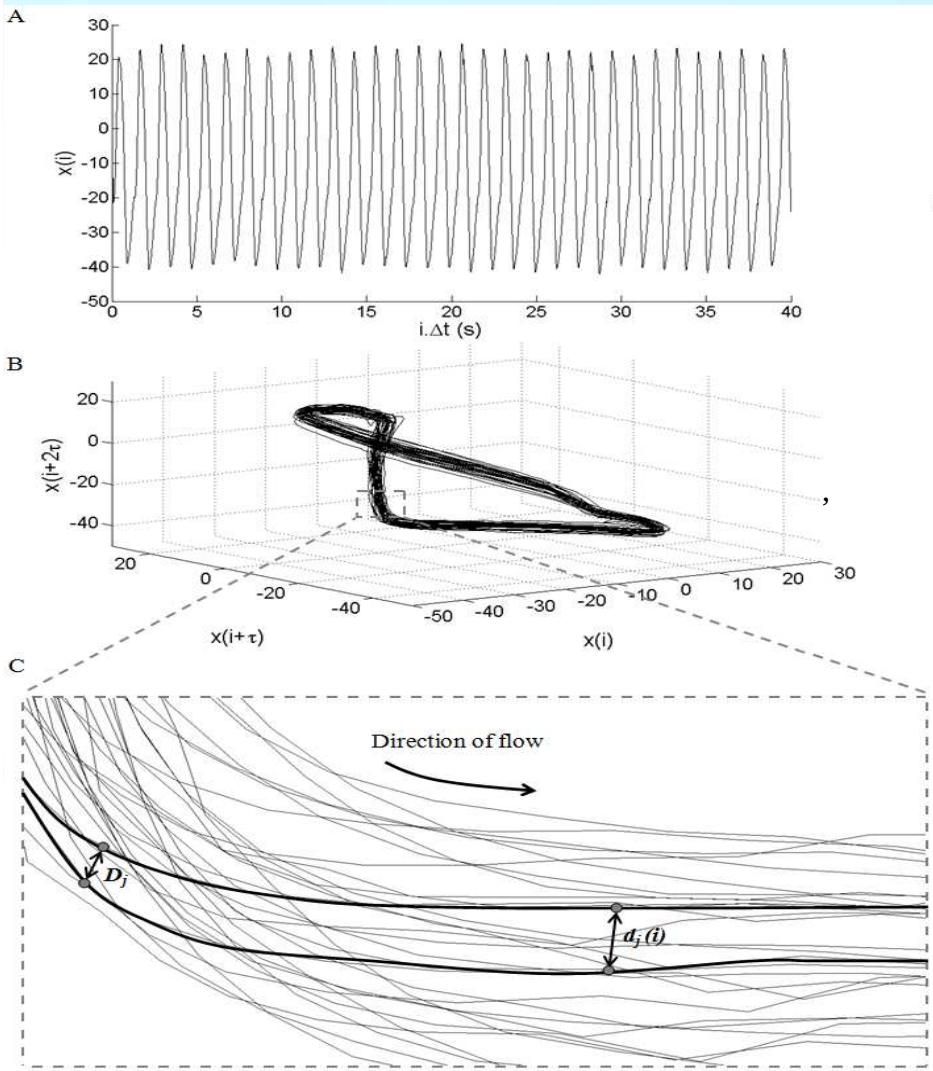


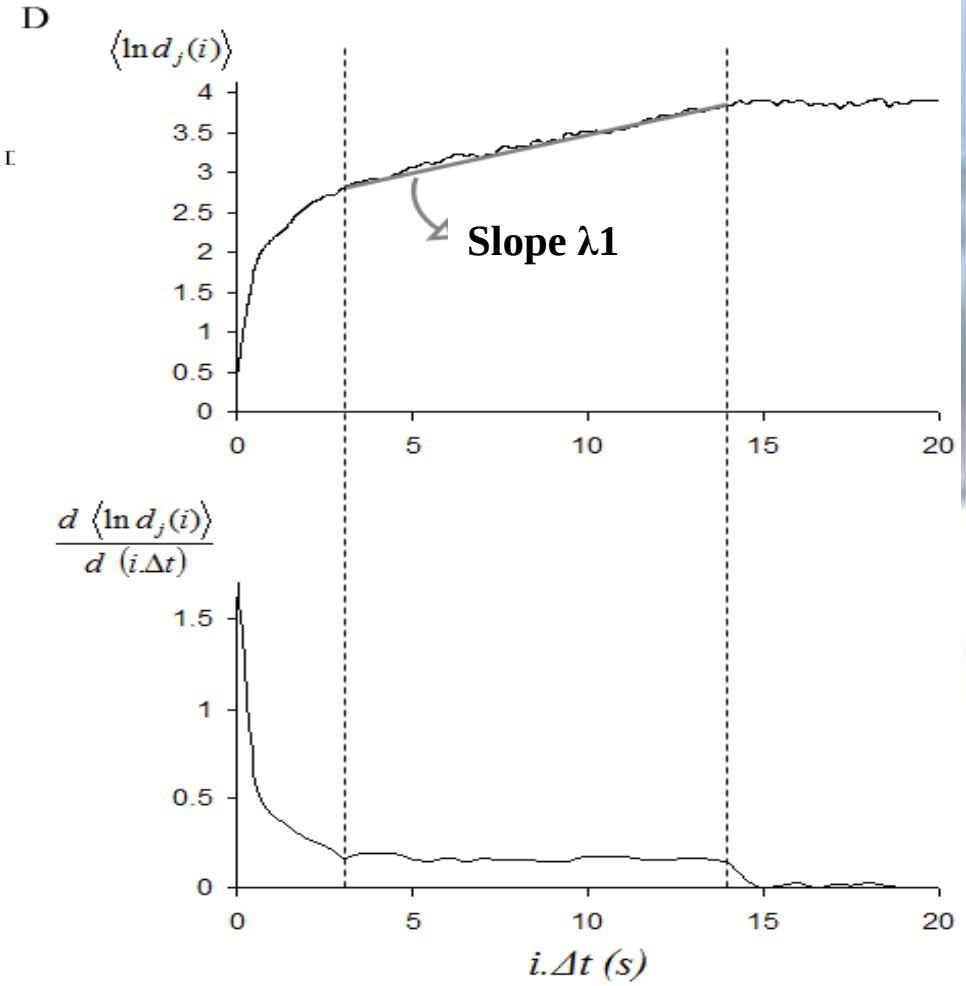
With fatigue Variability ↗

Type of variability: random or deterministic?

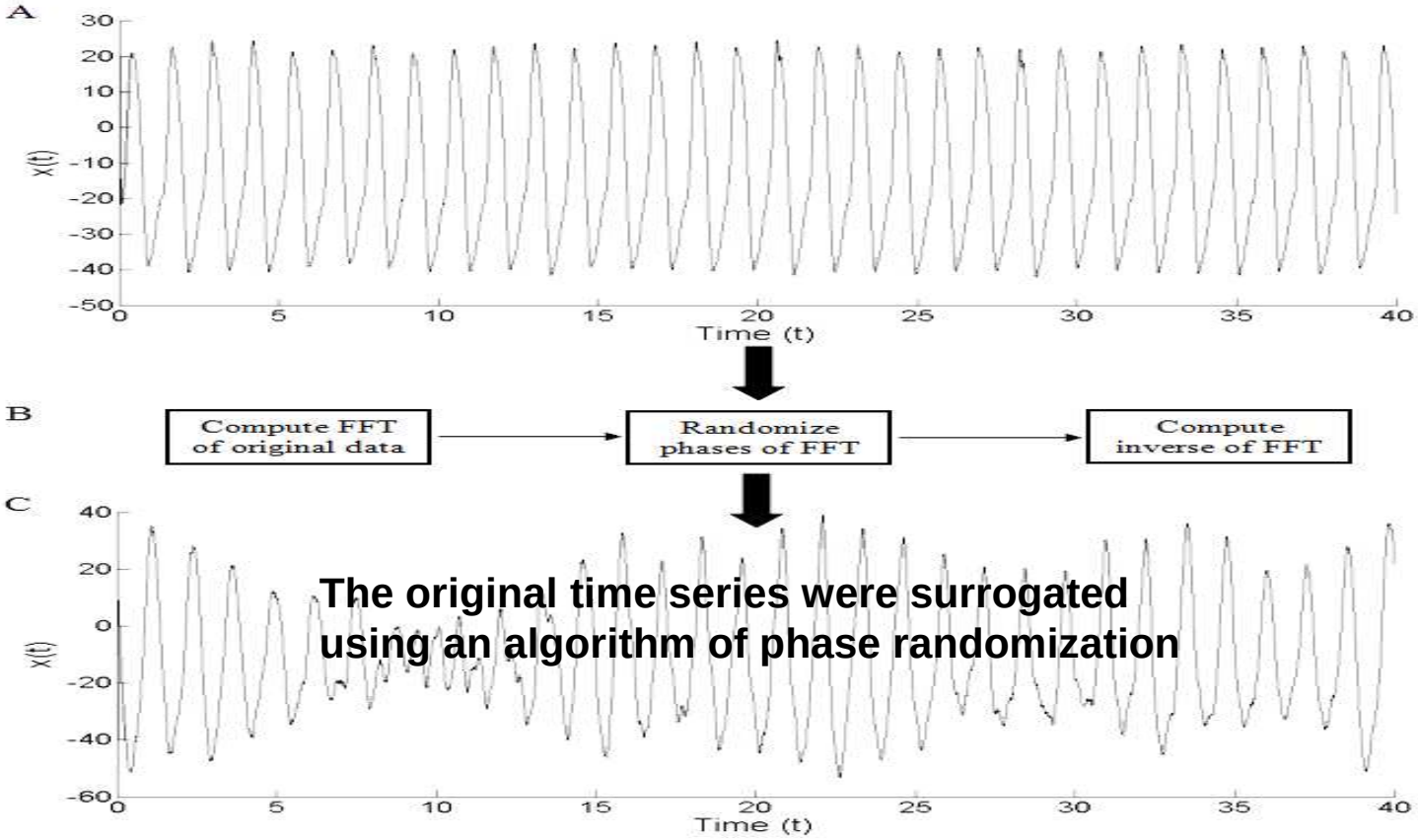
- The largest Lyapunov λ_1 exponent measures the average exponential rate of divergence of neighbouring trajectories of the attractor

λ_1 >0, higher exponents for the random systems





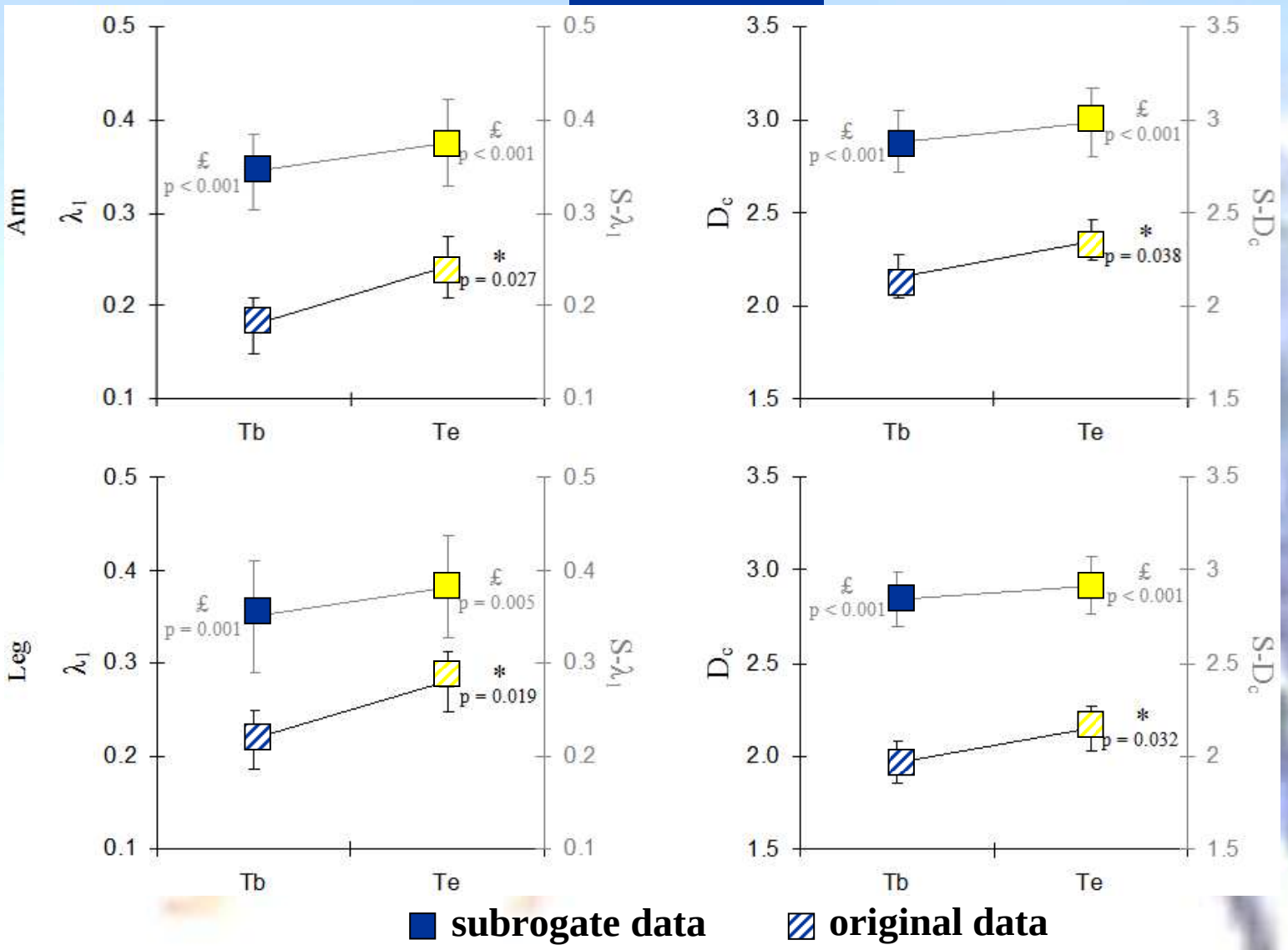
Verification of the kind of variability



▪ chaotic variability ? ⇔differences in λ_1 and D_c between the original data and their surrogate counterparts (Mann-Whitney tests)

▪ influence of fatigue on the kind of variability ? ⇔ differences in λ_1 and D_c between Tb and Te (Wilcoxon signed rank tests)

Results



With fatigue: λ_1 Dc ↗ ⇔ more random variability

Conclusions

- The fatigue constraint induced a re-parameterization of the model, reflecting a progressive modification of the control strategy of the leg movements

- With fatigue, the dropping influence of the damping terms lead to more sinusoidal (i.e., harmonic) velocity profiles which agree with an economic principle for movement control

The increase of stiffness indicated an increase of the movement frequency, to preserve constant the velocity of the exercise

- The fatigue constraint induced an increase of inter-cycle variability and more random variability, reflecting an alteration of the neuromuscular control mechanisms.

Practical applications

- **DST give a global information about the coordination of the neuromuscular system in cross country skiing**

- **Results indicated the degree of flexibility of the neuromuscular system which decreased with the fatigue making the skier less adaptable.**

- **This novel perspective would be interesting to differentiate skiers of different expertise level and should contribute to optimize the performance of the cross-country skier**

Thanks for your attention!