Science & Cycling
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An optimal control approach to the high intensity interval training design

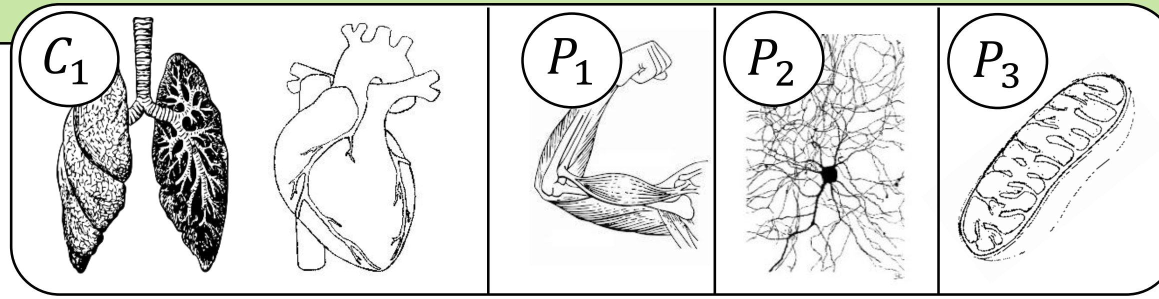
A. Zignoli[1,2], A. Fornasiero[1,2], A. Savoldelli[1,2], M. Morelli[3], E. Bertolazzi[1,2], F. Biral[3], B. Pellegrini[1,2]

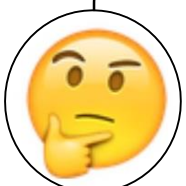
1. CeRiSM Research Center, University of Verona, Rovereto, Italy
2. Department of Neurological and Movement Science, University of Verona, Verona, Italy
3. Department of Industrial Engineering, University of Trento, Trento, Italy

Caen,
Wednesday, Jun 29th, 2016

1. Several factors limit the aerobic performance. The greatest improvements tend to be achieved with training and **HIT** is a time-efficient training tool.

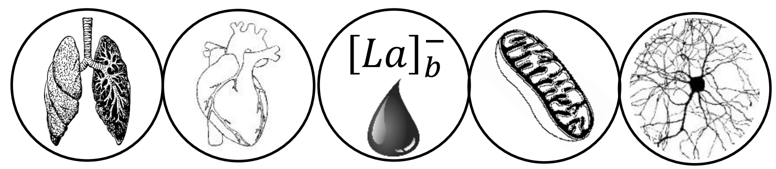
2. **Acute** physiological response to HIT can involve both peripheral (P) and central (C) adaptations.





$$n \times (t_w : t_r)@(P_w : P_r) = ?$$

t_w n P_w t_b t_r N P_b P_r



3. The subsequent adaptations that occur appear to be **specific** to the characteristics of the program employed

Seiler, *What is best practice for training intensity and duration distribution in endurance athletes*, *Int J Sports Physiol Perform*, 2010

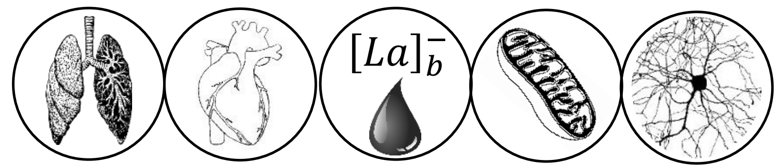
Laursen and Jenkins, *The scientific basis for high-intensity interval training*, *Sports Medicine*, 2013

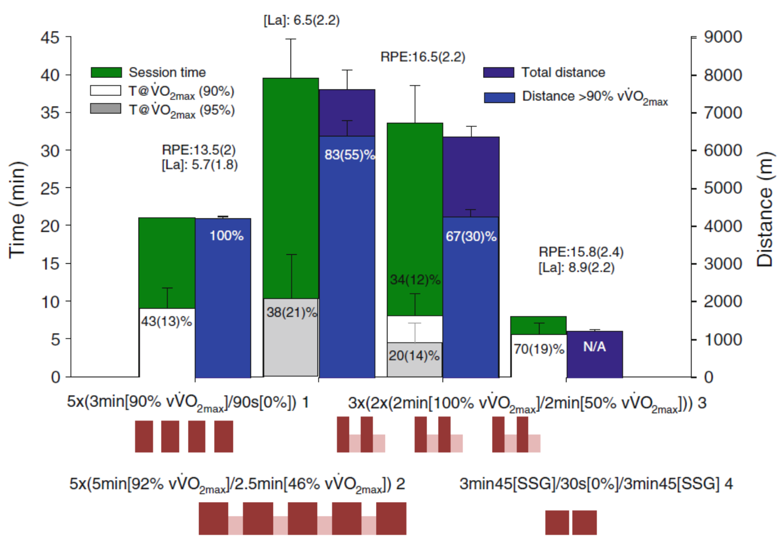
1 Kind of HIT that we want to investigate?

Aerobic involvement

$$n \times (t_w : t_r)@(P_w : P_r) = ?$$

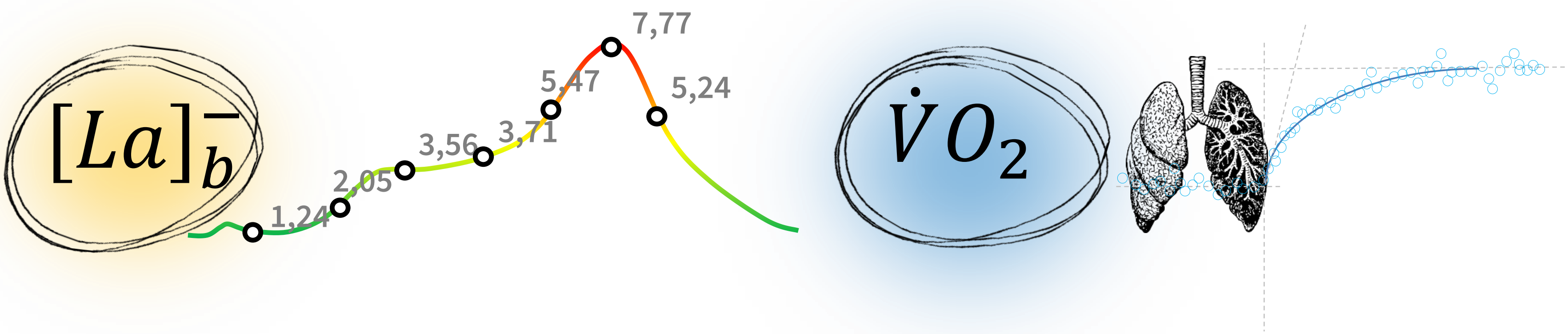
t_w n P_w t_b t_r N P_b P_r





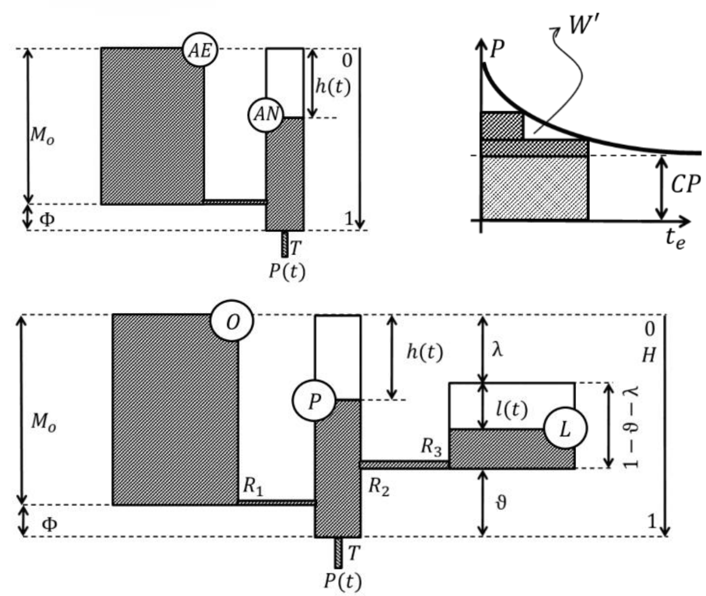
Buchheit and Laursen, *HIT Solutions to the Programming Puzzle, Sports Medicine, 2013*

1 Indicators for the physiological response to exercise



1

2

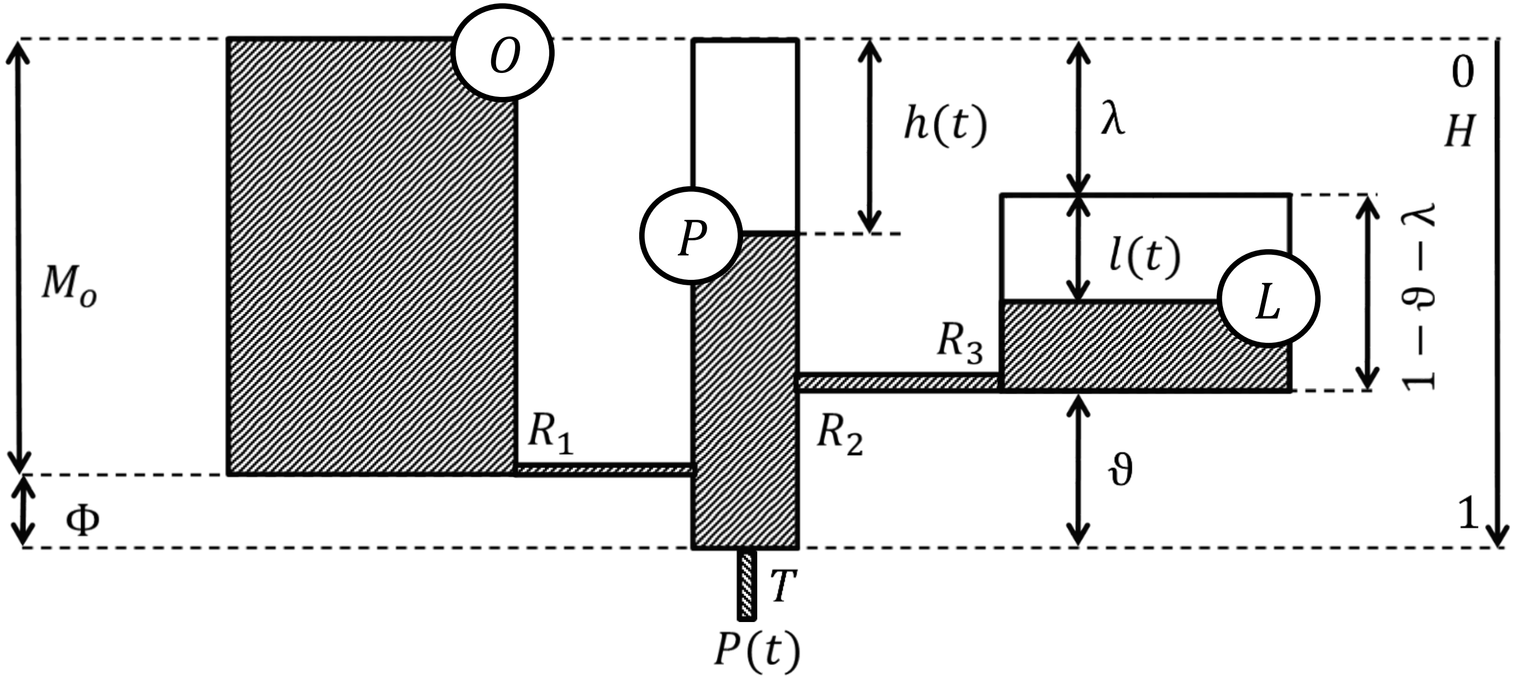


Morton, *The critical power and related whole-body bioenergetic models, EJAP*, 2006.

Authorship	Protocol	$[La]_b$ [mM]	t@90%VO_{2MAX}
Buchheit 2012	5x (3':90'')@(90:0)%VO_{2MAX}	5.7	544
Bjorklund 2007	tLIM(180'':360'')@(90:70)%VO_{2MAX}	6,7	NA
Dupont 2002	t_{LIM}(15'':15'')@(110:0)%VO_{2MAX}	11.1	383
	t_{LIM}(15'':15'')@(120:0)%VO_{2MAX}	13.1	323
	t_{LIM}(15'':15'')@(130:0)%VO_{2MAX}	14.7	135
	t_{LIM}(15'':15'')@(140:0)%VO_{2MAX}	13.5	77
Millet 2003	3x$t_{LIM-MAV}$(3x(30'':30'')@(100:50)%VO_{2MAX})300''	NA	149
	3x$t_{LIM-MAV}$(3x(60'':30'')@(100:50)%VO_{2MAX})300''	NA	531
Nicolò 2014	t_{LIM}(30'':30'')@(135:0)%VO_{2MAX}	10	259
	t_{LIM}(40'':20'')@(135:0)%VO_{2MAX}	13	401
Ronnestad 2013	t_{LIM}(30'':15'')@(100:50)%VO_{2MAX}	13	678
Ronnestad 2015	3x(13x30'':15'')@(100:50)%VO_{2MAX})180''@50%VO_{2MAX}	11.4	NA
Tardieu 2004	t_{LIM}(30'':30'')@(110:50)%VO_{2MAX}	10.7	345
	t_{LIM}(6x((30'':30'')@(110:50)%VO_{2MAX})240''	11.5	290
Thevenet 2007	t_{LIM}(30'':30'')@(105:50)%VO_{2MAX}	NA	746
	t_{LIM} (30'':15'')@(105:0)%VO_{2MAX}	NA	548
Vuorimaa 2000	14x(1':1')@(100:0)%VO_{2MAX}	4.8	NA
	7x(2':2')@(100:0)%VO_{2MAX}	8.8	NA
Wakefield 2009	t_{LIM}(30'':20'')@(115:50)VO_{2MAX}	6.1	80 (@95%)
	t_{LIM}(25'':20'')@(115:50)VO_{2MAX}	4.75	38
	t_{LIM}(20'':20'')@(115:50)VO_{2MAX}	4.3	26
	t_{LIM}(30'':20'')@(105:50)VO_{2MAX}	3.5	153
	t_{LIM}(25'':20'')@(105:50)VO_{2MAX}	2.8	60
	t_{LIM}(20'':20'')@(105:50)VO_{2MAX}	2.6	41
Stepto 2001	8x(5':1')@(86:<30)%VO_{2MAX}	5,8	NA

1

Morton Margaria model (MM3)



2

3. Model configurations

There are in fact sixteen configurations of the generalised M-M model, depending on whether ϕ and/or θ and/or λ are or are not zero; and whether λ is greater than, equal to or less than ϕ; and/or θ is greater than, equal to or less than $1-\phi$. Margaria's (1976) original is the particular case when $\lambda = 0$ and $\phi = \theta = \frac{1}{2}$. The sixteen configurations can be reduced to four, by eliminating those inconsistent with known physiological facts.

Morton, A three component model of human bioenergetics, *J math bio*, 1986.

Participants' characteristics N=8 (7M, 1F)	$\dot{V}O_{2MAX}$ [mlO_2/min kg_{bw}]	PPO [W/kg_{bw}]	P1 [W]	P2 [W]	P3 [W]
μ	57	4,4	111	248	306
SD	10,2	0,7	20,5	39,5	40,8

1

Incremental to exhaustion test

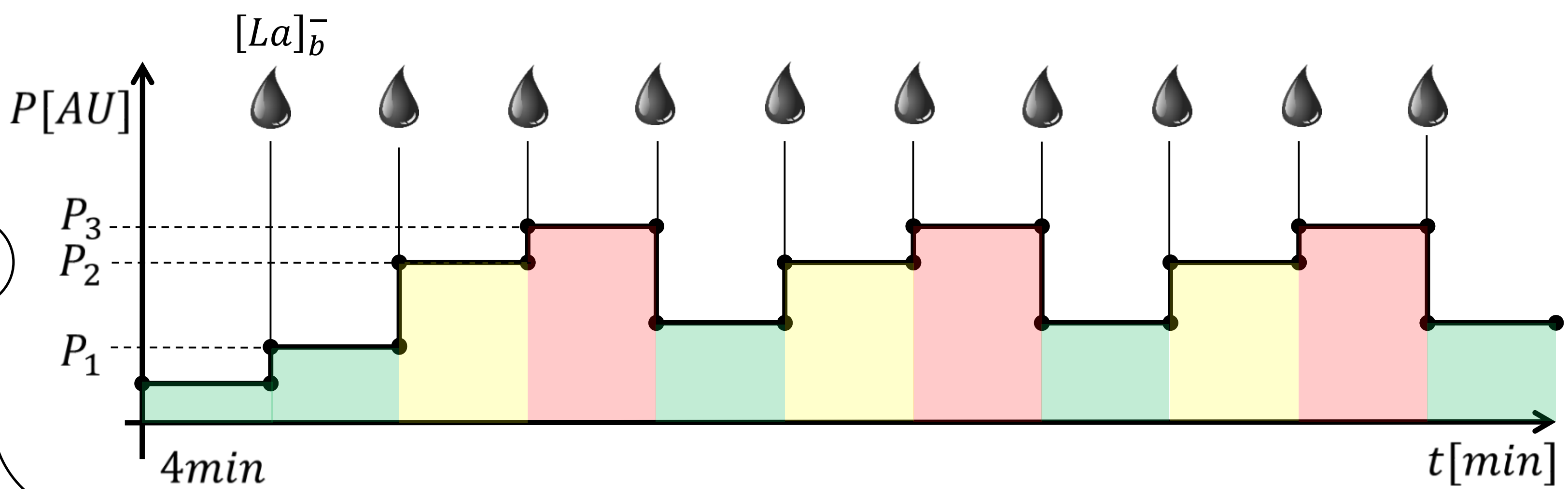
P1(50%PVT1) MODERATE

P2(50%PVT1-2) HEAVY

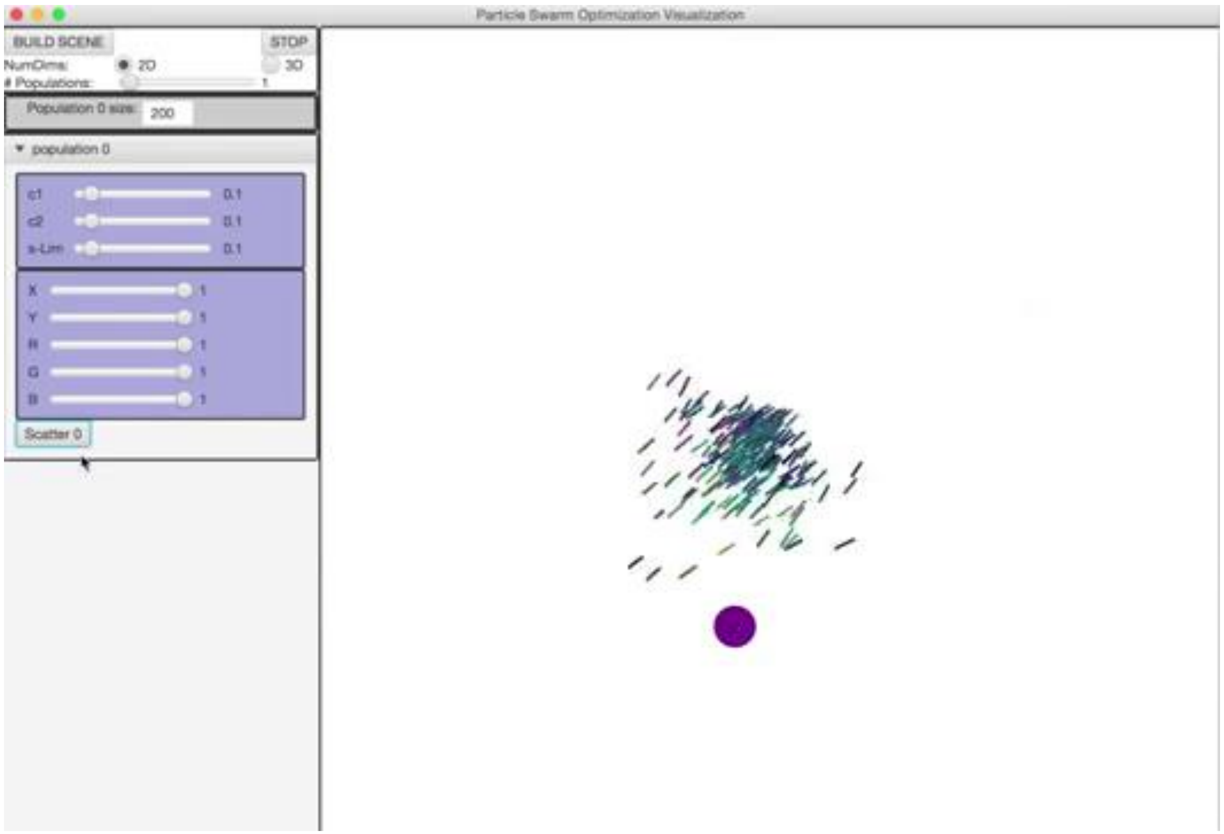
P3((50%PVT1-PVO2max)) SEVERE

2

Generically shaped protocol



1 Particle Swarm Optimization (PSO)

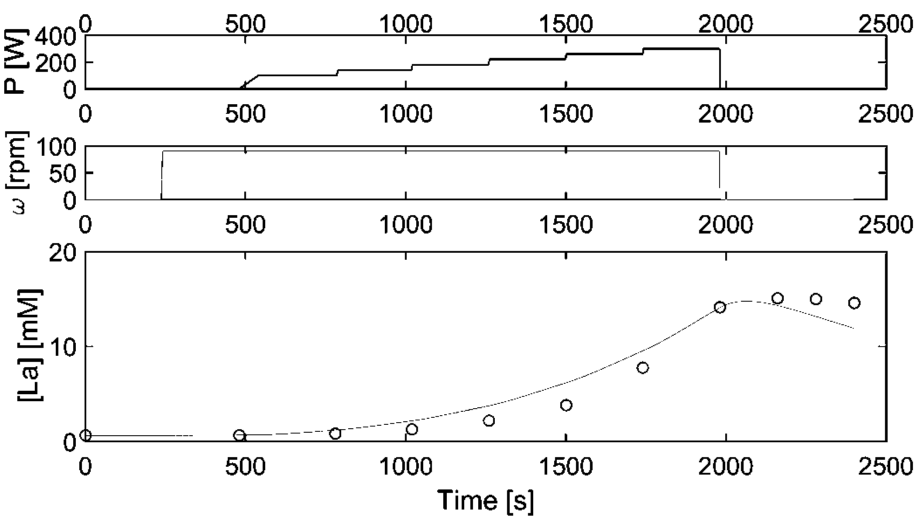


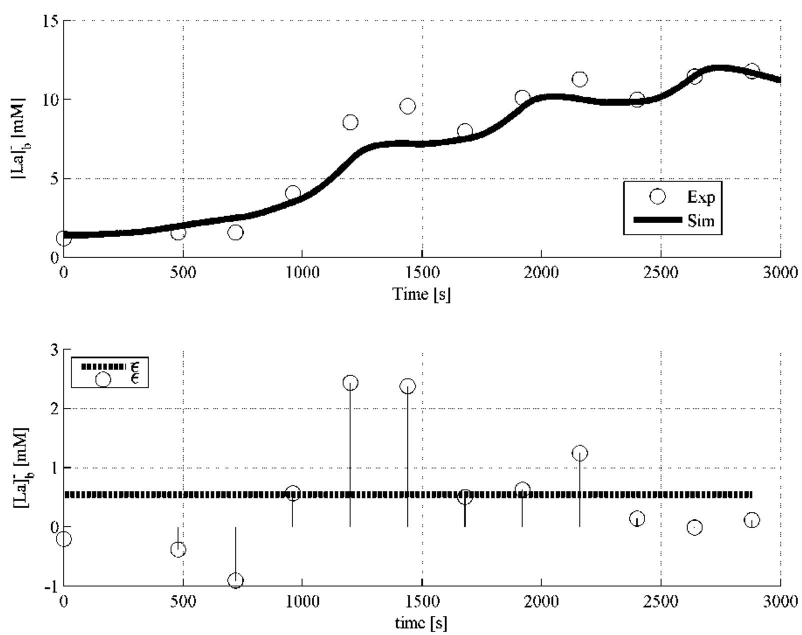
Kennedy, J. and Eberhart, *Particle swarm optimization*, IEEE Int Conf NN, 1995

Blood lactate concentration dynamics model

	States	Parameters	Inputs	Outputs
Model	x	p	u	y
Morton	$[La]_b^-$	$\lambda, \ldots$	P, ω	$[La]_b^-, \dot{V}O_2$

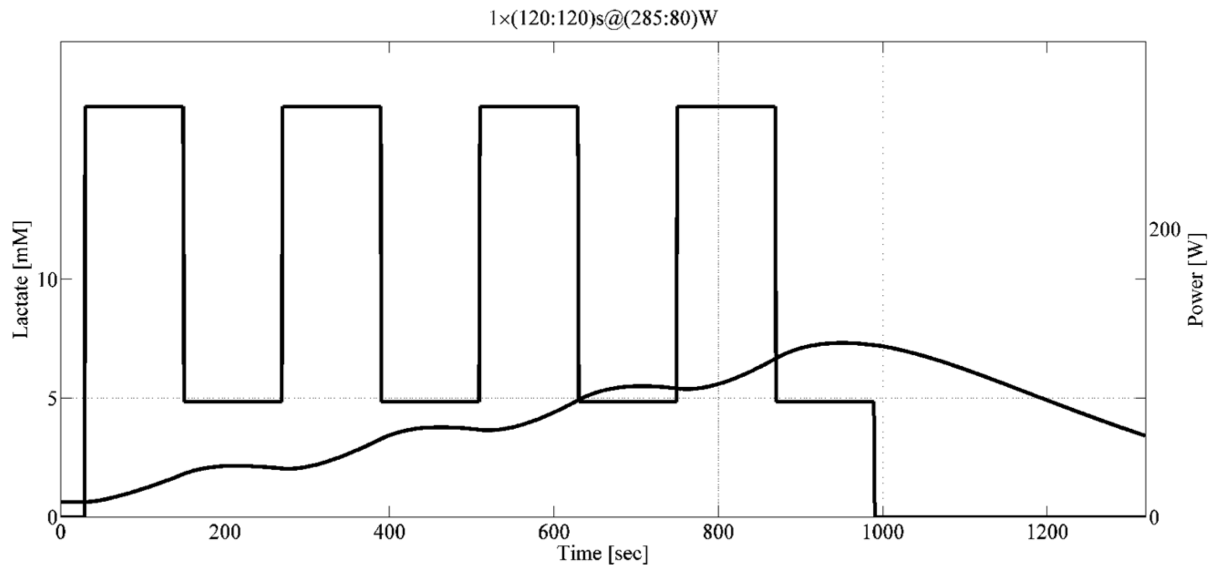
R^2	ε [mM]	RMSE [mM]
0,91	0,54	3,89

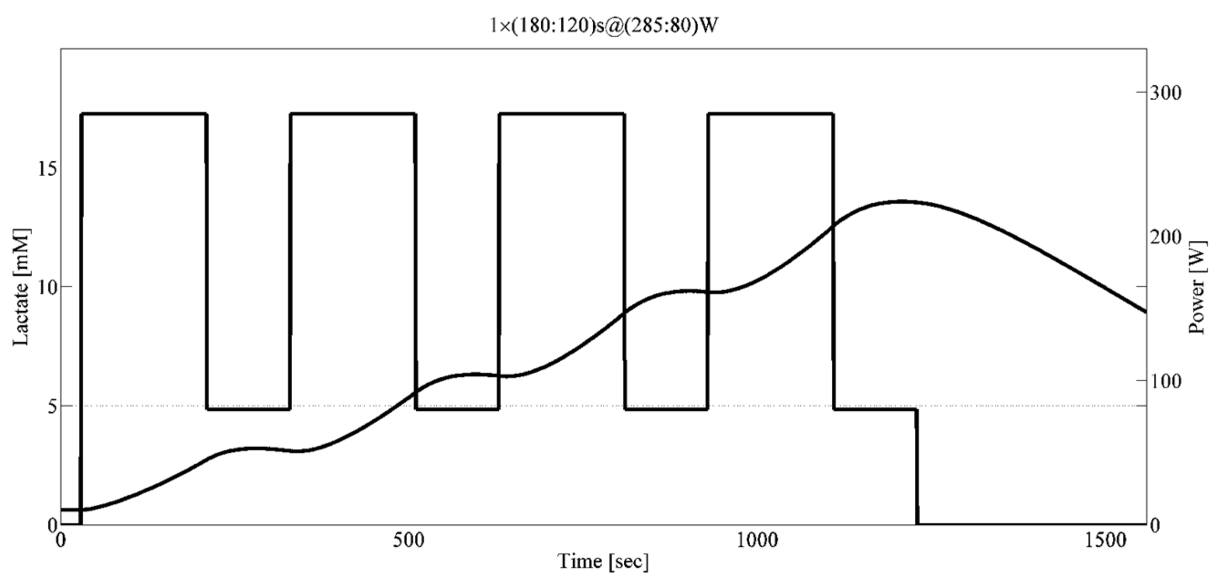




1 Open-loop simulations

Athlete
IZ
$\dot{V}O_{2MAX}$ [mlO_2/min kg_{bw}]
50
PPO [W]
300
W' [kJ]
22





1 What is the combinatio that **maximize** the stimuli without leading to **premature exhaustion** while expressing the **maximal capacity** of the athlete

2 We can formulate the **HIT** problem as an **optimal control problem** in which the objective function maximize some target

3 Improvements in VO_{2MAX} might be optimized when you perform as much training as possible at intensities near VO_{2MAX}

3

$$L = \int \left(\left(\frac{\dot{V}O_{2MAX}}{\Delta \dot{V}O_2} \right)^2 + \left(\frac{[La]_b}{\Delta [La]_b} \right)^2 + \lambda[\Phi] \right) dt$$

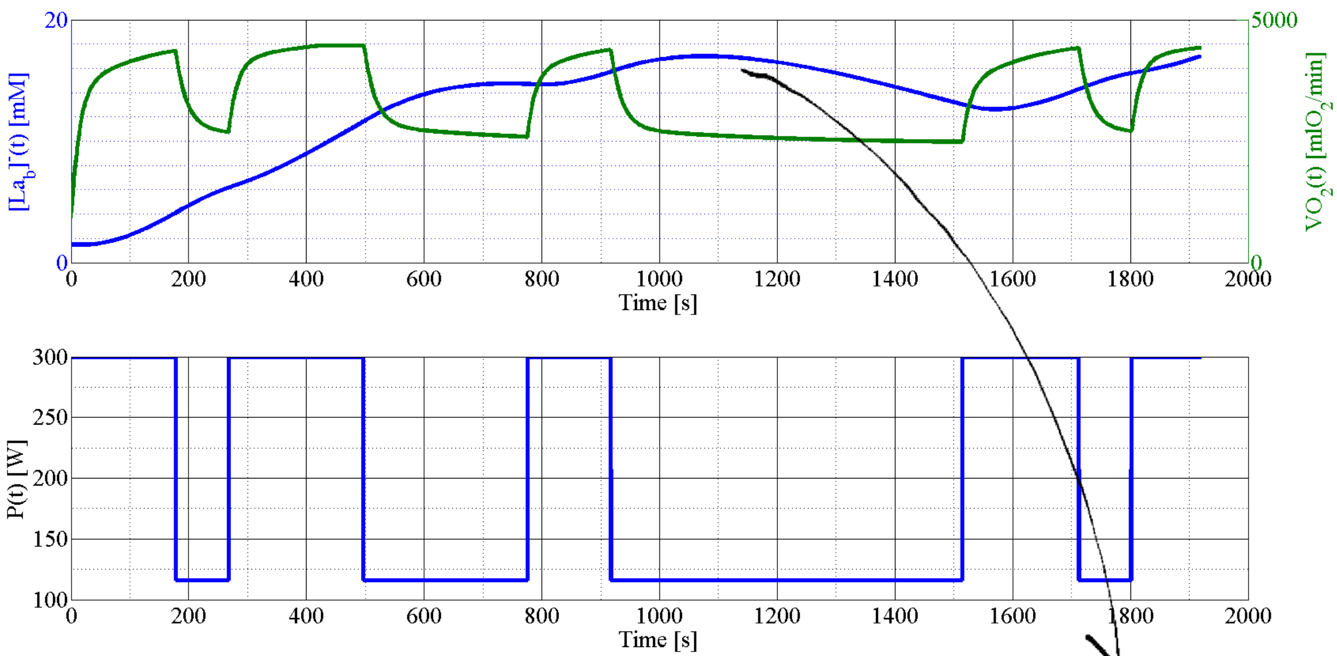
e.g. maximize **t@90%$\dot{V}O_{2MAX}$**… but alsways **respecting constrains** (i.e. the equation of the model).

Bertolazzi et al., *Symbolic–numeric indirect method for solving optimal control problems for large multibody systems*, Multibody Sys. Dyn., 2005;

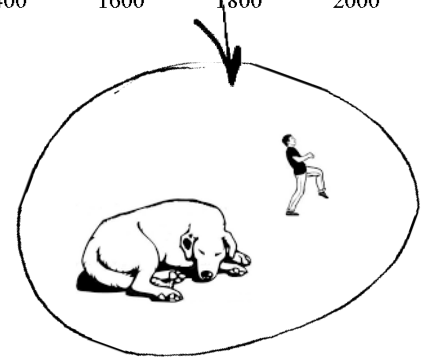
Buchheit and Laursen, *HIT Solutions to the Programming Puzzle, Sports Medicine, 2013*

Athlete	$\dot{V}O_{2MAX}$ [mlO_2/min kg_{bw}]	PPO [W]	W' [kJ]
IZ	50	300	22

180'', 90'', 210'', 210'', 140'', 540'', 210'', 90'', 180''

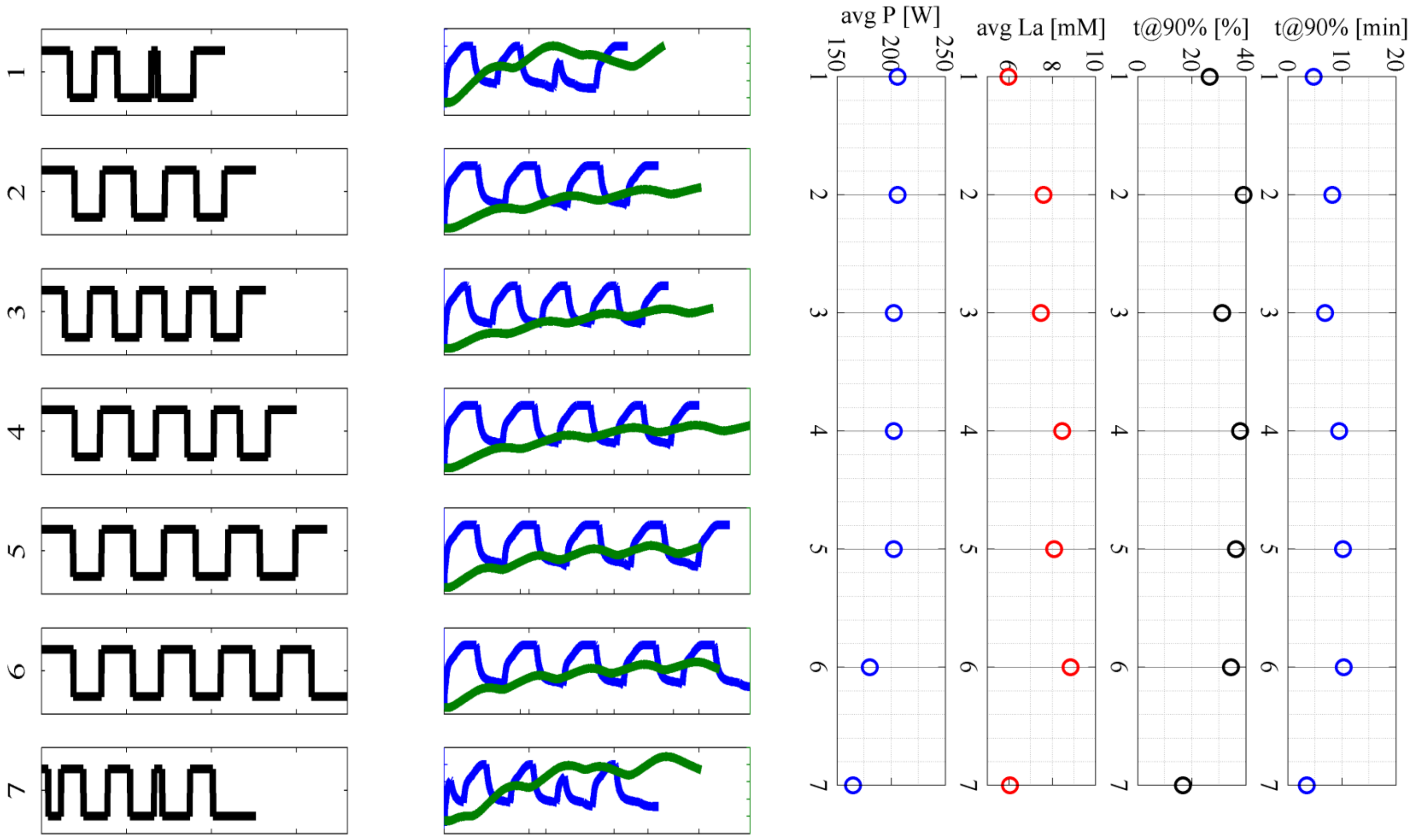


$T@VO_{2max90\%} \approx 10$ min and
$\%T@VO_{2max90\%} \approx 30\%$
$P_w = 100\%PVO_{2max}$
P(t) ~218 W.



1 How many open-loop simulations can I try?

Theory and practice hold that in such protocols there is an increase in the aerobic energy system involvement as the session progresses, while blood lactate concentration appear to reach somewhat of an equilibrium during such training



1 Key messages: the theory

With individualized parameters it is possible to estimate the response of the athlete to the induced metabolic load and then to generate more time-efficient and more effective training sessions.

Mathematical models and optimal control can offer a valid contribution in a systematic approach to the HIT design in cycling as they can handle the complexity of parameters that usually show mutual interaction.

The method suggests that the best solution may lie in protocols in which working and recovery time intervals are not constant across the exercise.

2 Key message: the practice

If it is the aerobic involvement you are looking for …

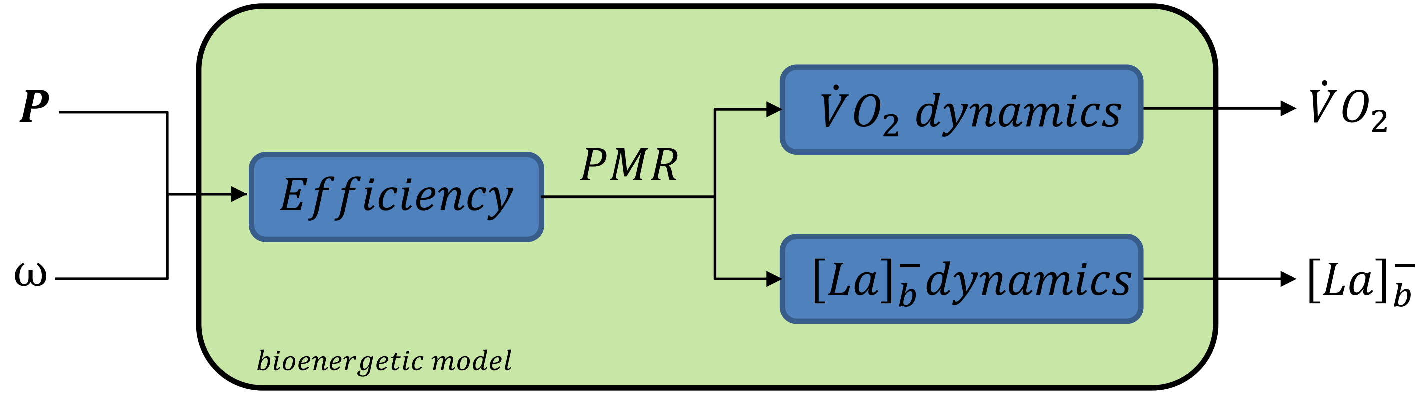
"Let the sleeping dog lie"

F.A.

Thank you

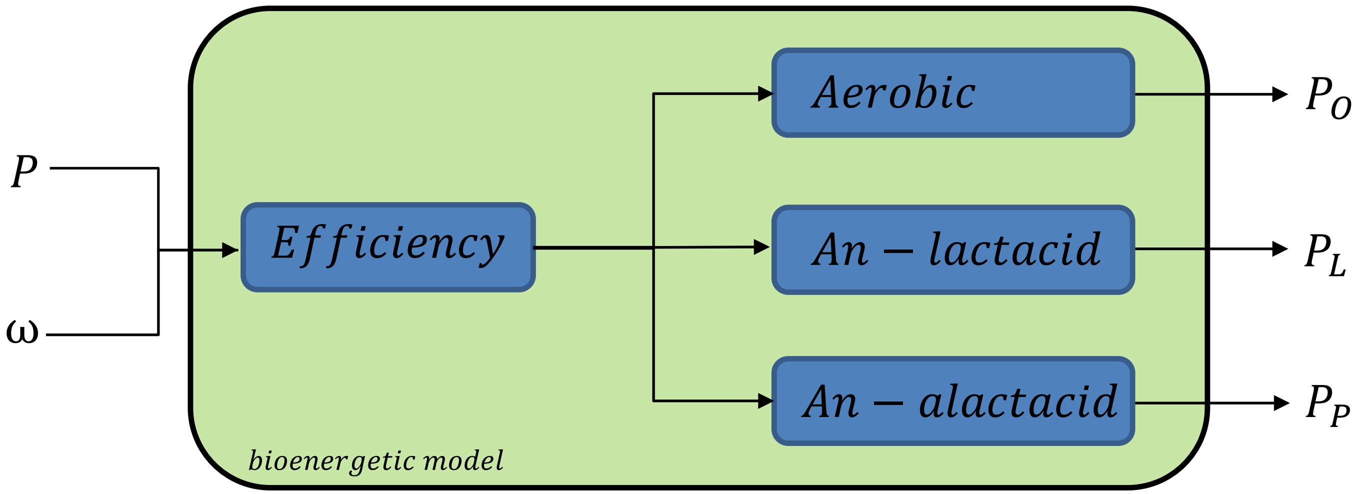
PI: A. Zignoli
andrea.zignoli@univr.it

Discussion



Oxygen dynamics model				
	States	Parameters	Inputs	Outputs
Model	x	p	u	y
First order	$\dot{V}O_2$	G	P	$\dot{V}O_2$
First order [W]-	$\dot{V}O_2$	G, K, τ, m_L	P, ω	$\dot{V}O_2$
First order 3-phase	$\dot{V}O_2$	G, TDI, $TDII$, τ	P	$\dot{V}O_2$

Blood lactate concentration dynamics model				
	States	Parameters	Inputs	Outputs
Model	x	p	u	y
Second order	$[La]_b^-$, $[\dot{La}]_b^-$	G, τ	Δ	$[La]_b^-$
Moxnes	$[La]_b^-$	α, β, τ, λ, …	P, ω	$[La]_b^-$, $\dot{V}O_2$
2-compartment	$[La]_b^-$, $[La]_m^-$	G, TDI, $TDII$	Δ	$[La]_b^-$

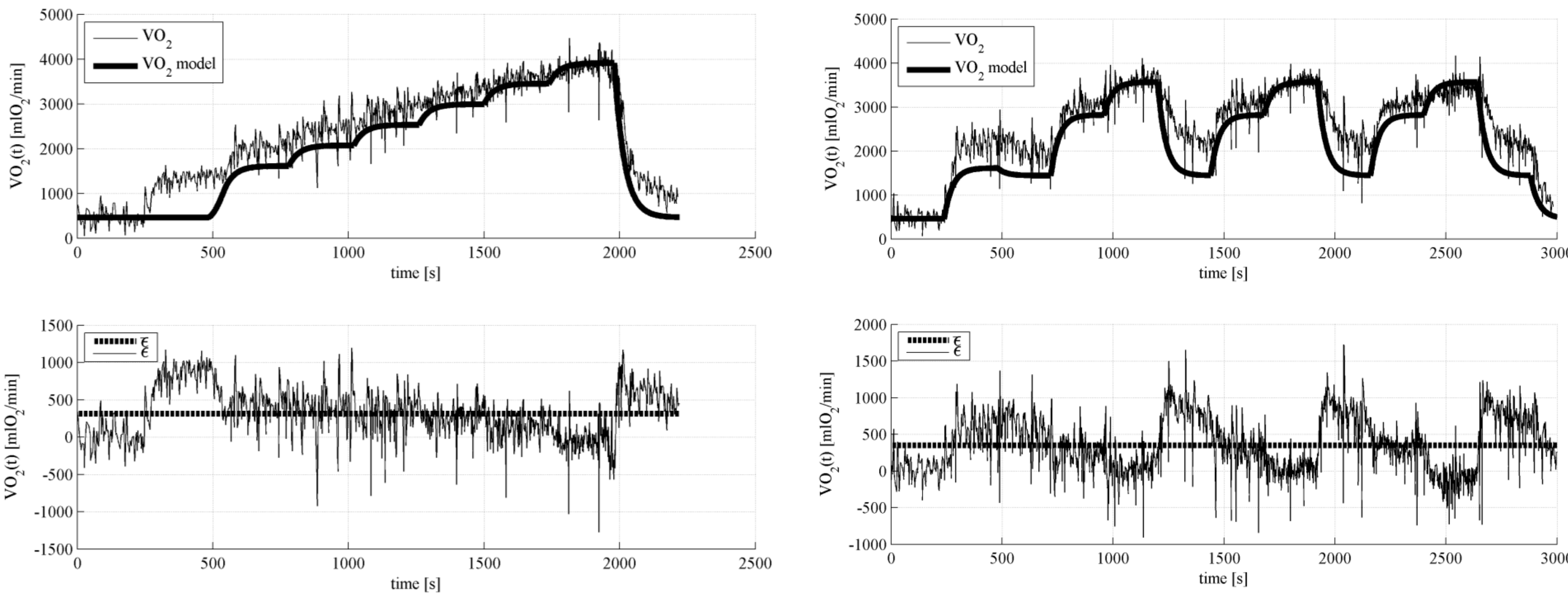


Energy production and depletion models				
	States	Parameters	Inputs	Outputs
Model	x	p	u	y
CP	AnS	CP, W'	P	AnS
MM-3	l, h	$\Phi, \psi, \lambda, \ldots$	P, ω	P_{AE}, P_L, P_P
MM-3 ext	$l, h, [La]_b^-, \dot{V}O_2$	$\tau, \lambda, \ldots$	P, ω	$[La]_b^-, \dot{V}O_2$


Interval Training for Endurance
CHAPTER 5
Interval Training for Endurance
Paul B. LAURSEN1,2,3
1High Performance Sport New Zealand, Auckland, New Zealand
2Sport Performance Research Institute New Zealand (SPRINZ), School of Sport and Recreation, Auckland University of Technology
Auckland, New Zealand
3School of Exercise, Biomedical and Health Sciences, Edith Cowan University, Joondalup, WA, Australia
Introduction
What Physiological Events Occur During a Single High Intensity Interval Training Session?

Oxygen dynamics model without internal work				
	States	Parameters	Inputs	Outputs
Model	x	p	u	y
First order	$\dot{V}O_2$	G	P	$\dot{V}O_2$

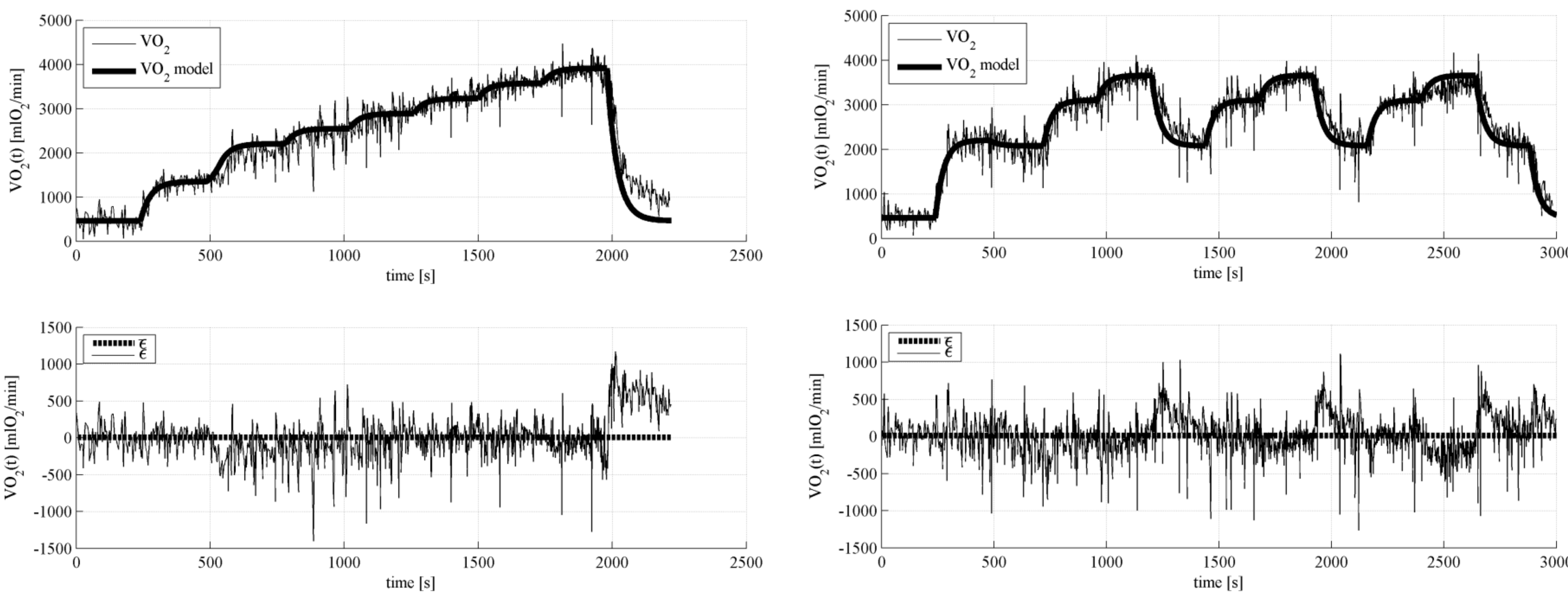
R^2	ε [mlO_2/min]	RMSE [mlO_2/min]
0,73	349	*515*

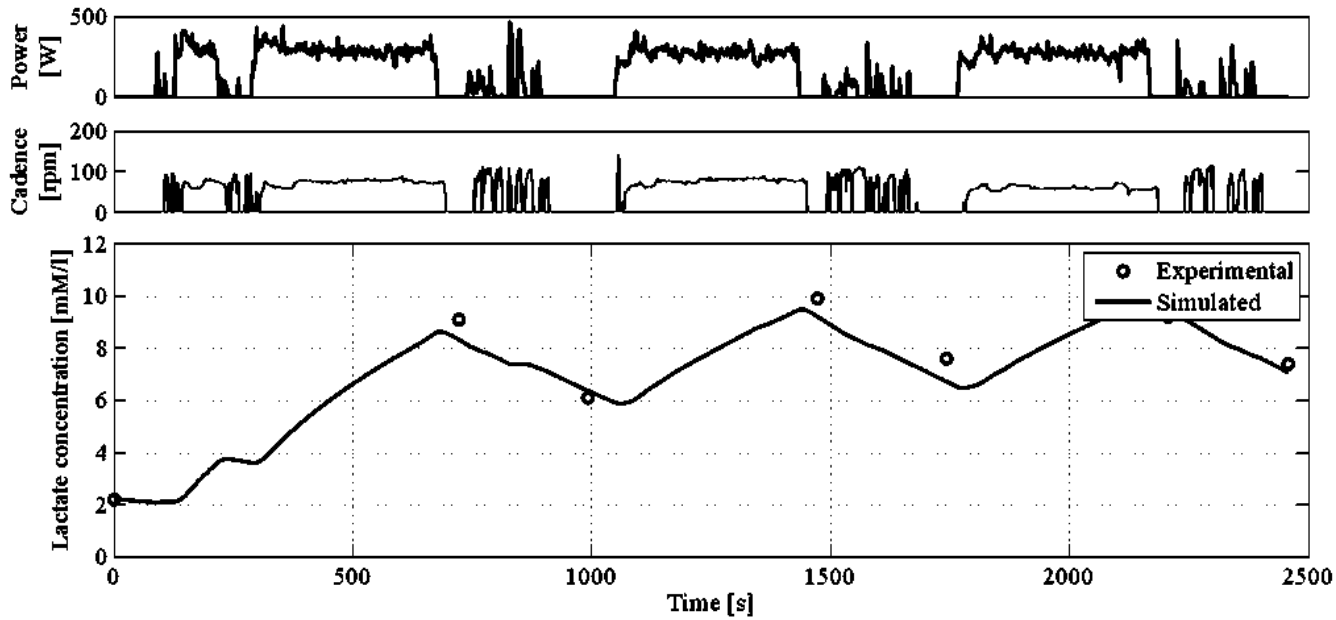


Oxygen dynamics model with internal work

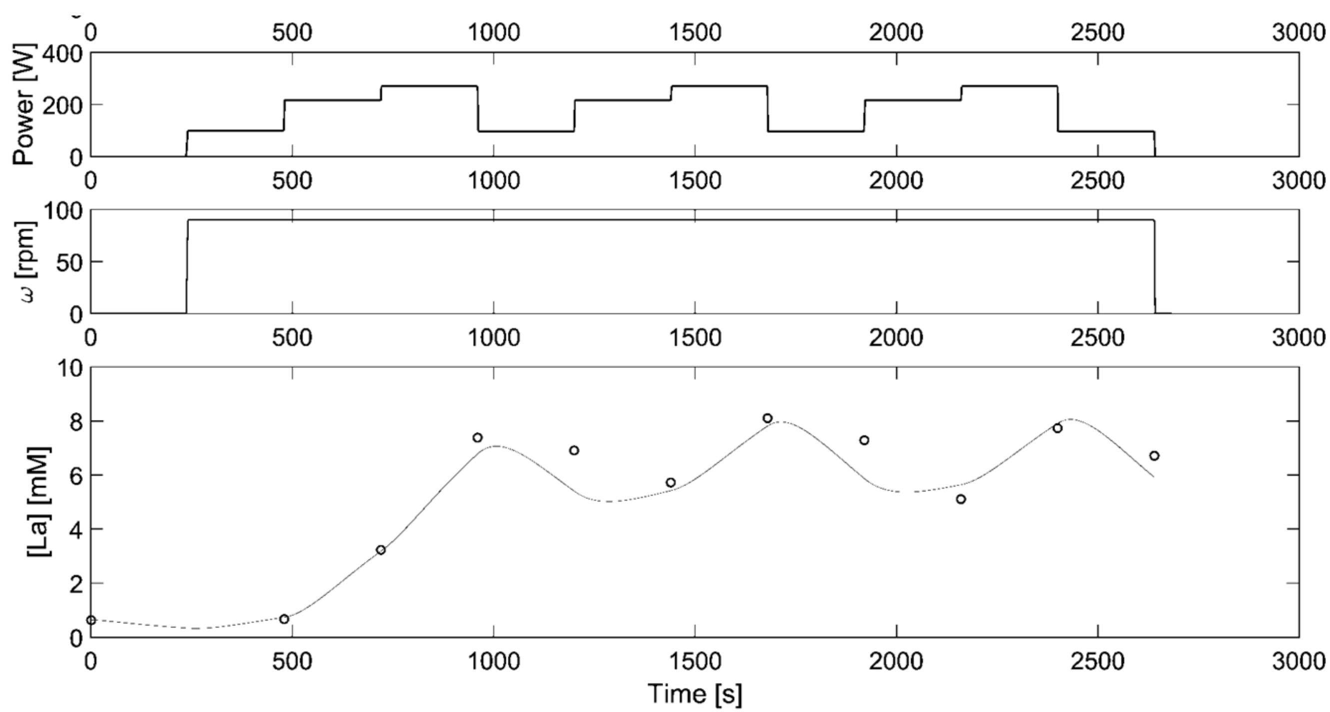
	States	Parameters	Inputs	Outputs
Model	x	p	u	y
First order	$\dot{V}O_2$	G, γ, KL	P, ω	$\dot{V}O_2$

R^2	ε [mlO_2/min]	RMSE [mlO_2/min]
0,89	10	*266*

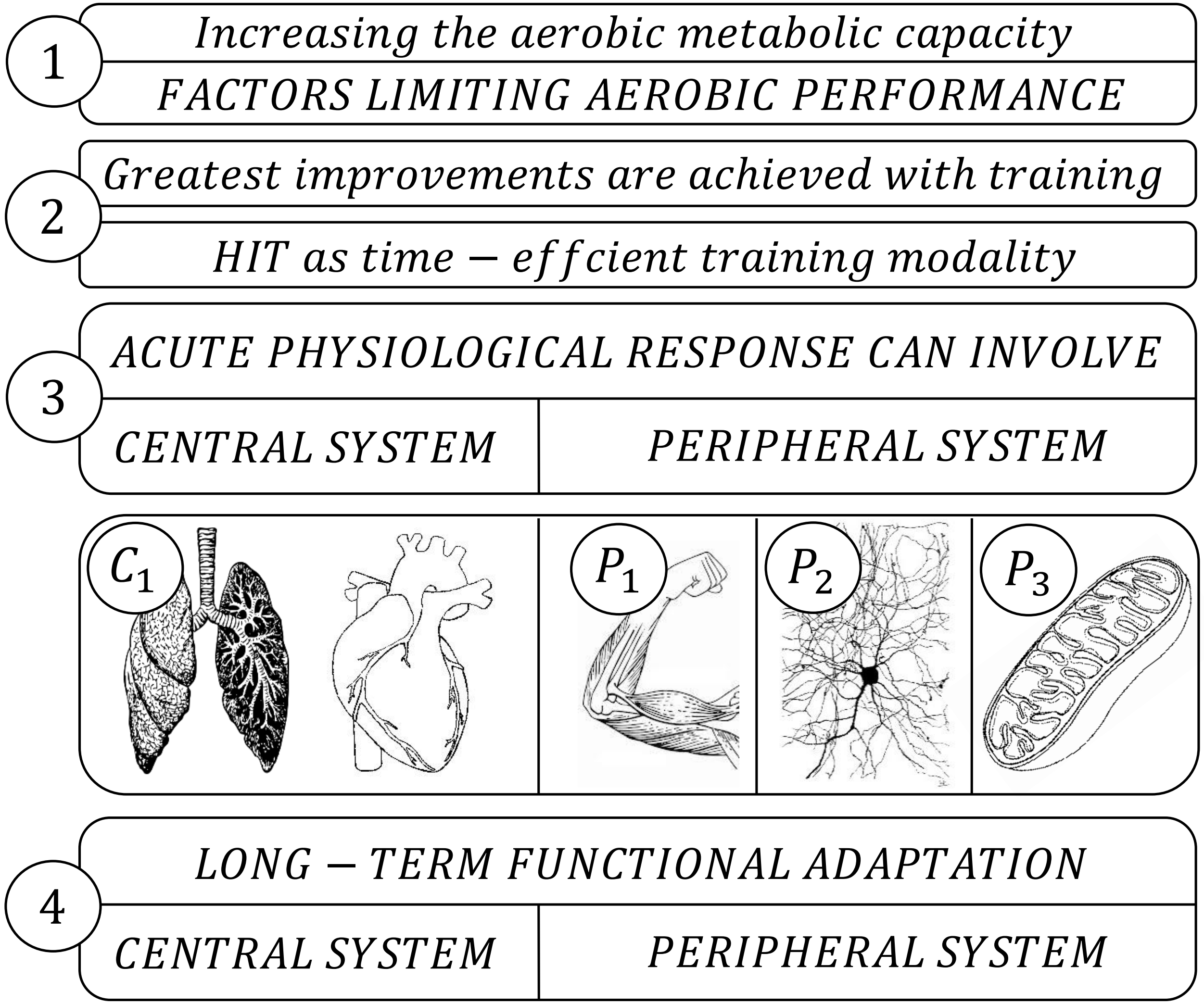




Power [W]
Cadence [rpm]
Lactate concentration [mM/l]
Experimental
Simulated
Time [s]



Power [W]
ω [rpm]
[La] [mM]
Time [s]


1
Increasing the aerobic metabolic capacity
FACTORS LIMITING AEROBIC PERFORMANCE
2
Greatest improvements are achieved with training
HIT as time − effcient training modality
3
ACUTE PHYSIOLOGICAL RESPONSE CAN INVOLVE
CENTRAL SYSTEM
PERIPHERAL SYSTEM
C_1
P_1
P_2
P_3
4
LONG − TERM FUNCTIONAL ADAPTATION
CENTRAL SYSTEM
PERIPHERAL SYSTEM

1

Bioenergetic models work fine for $\dot{V}O_2$ and $[La]_b^-$.*
If we feel confident enough we can use them for challenging the HIT programming puzzle.
*they have to be calibrated on purpose

2

Predictive dynamics of cycling can be afforded by optimal control algorithm in reasonable amount of CPU time.
Endless list of *what if* scenarios.

3

Computationally effcient models can be used along with optimal control in the pacing strategy solution.
Not only in races but also on pedaling assisted bikes.




University of Verona

research center - Rovereto (TN) CeRiSM sport mountain health

MECHATRONIC SYSTEM MODELLING
MECHATRONICS RESEARCH GROUP
UNIVERSITY OF TRENTO - Italy

UNIVERSITY OF CALGARY

«You should grow up a garden, not a national park.»
BP.2013

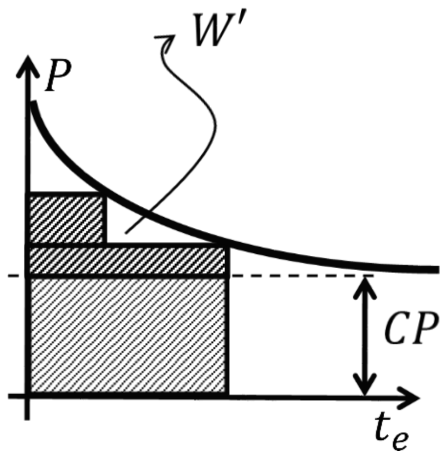
«We can do that. It’s only matter of time and passion.»
FB.2011

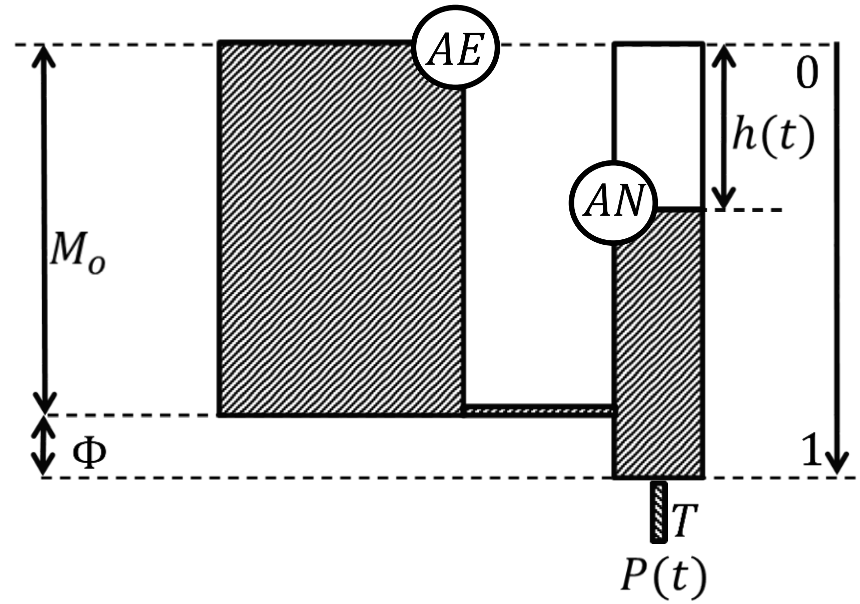
«There is a big difference between someone who works a lot and someone who’s always busy»
WH.2015

1

Critical power model (MM2)

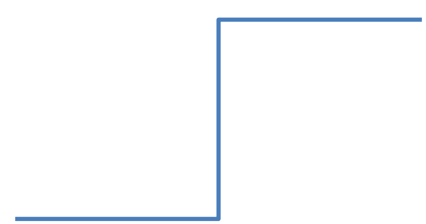
Moritani et al., *Critical power as a measure of physical work capacity and anaerobic threshold, Ergonomics, 1981*
Morton, *The critical power and related whole-body bioenergetic models, EJAP*, 2006.

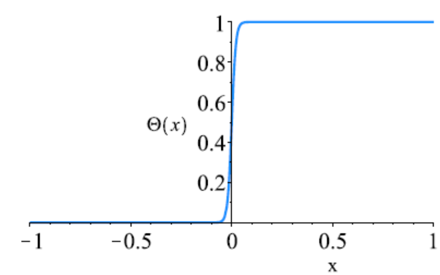


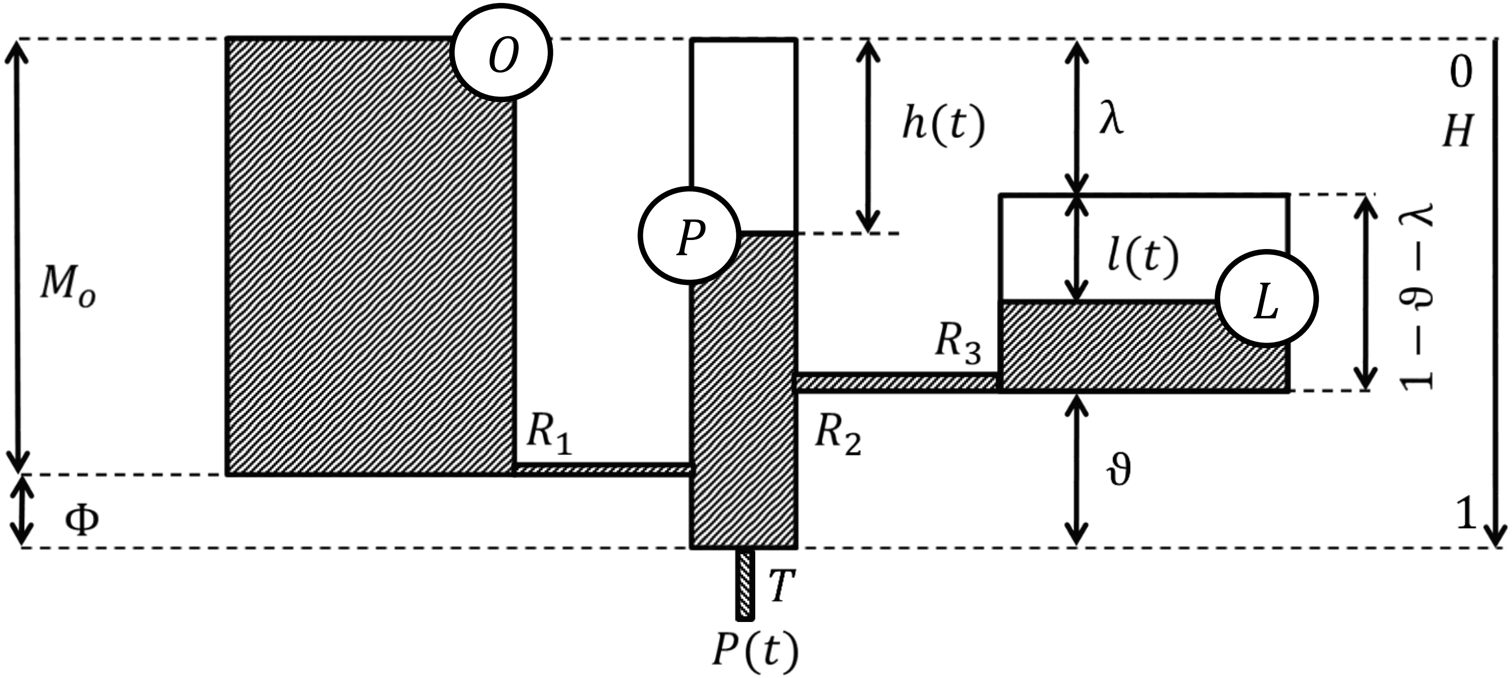


2

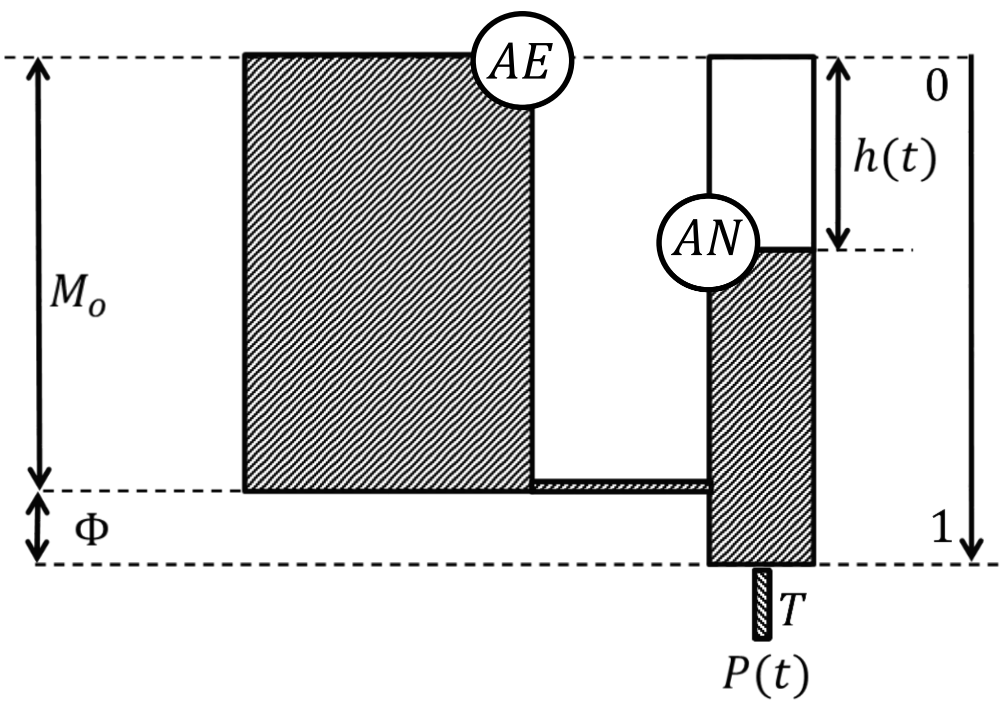
```
...
if P > CP
    do this
       and that
end
...
```







O
P
L
h(t)
λ
l(t)
0
H
1 − ϑ − λ
M_o
R_1
R_2
R_3
ϑ
Φ
1
T
P(t)



AE
AN
h(t)
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M_o
Φ
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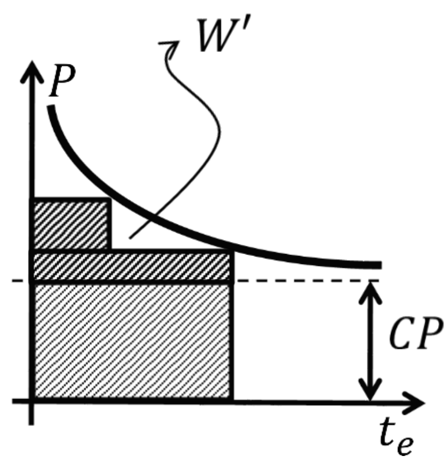
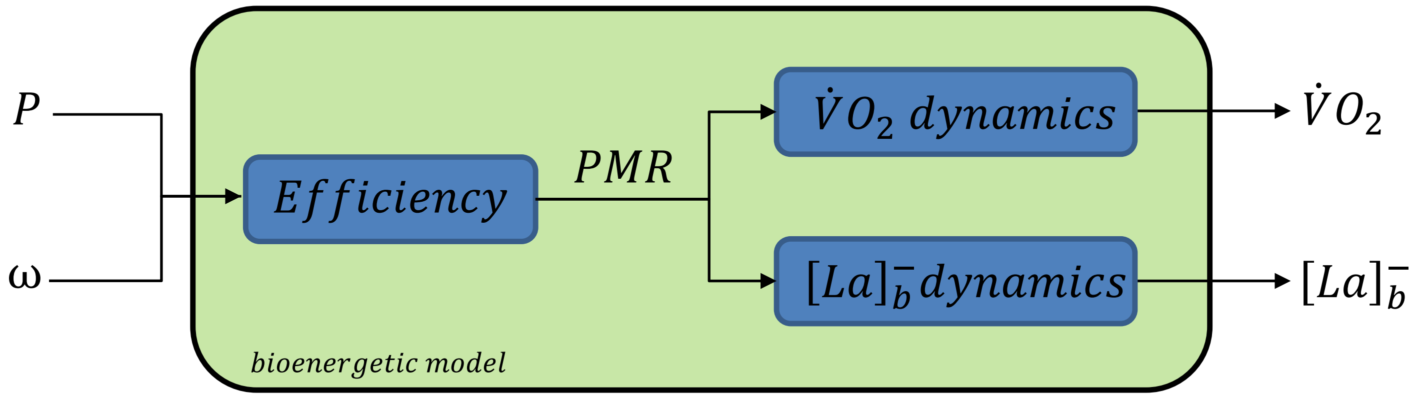
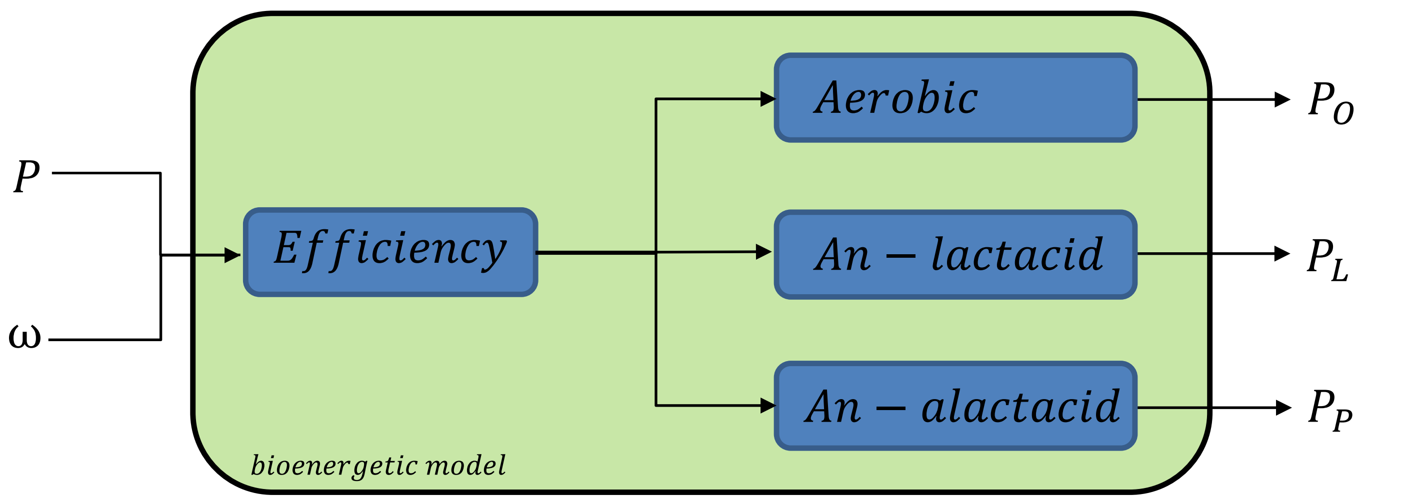
P(t)



P
W′
CP
t_e


P
ω
Efficiency
PMR
$\dot{V}O_2$ dynamics
$[La]_b^-$ dynamics
$\dot{V}O_2$
$[La]_b^-$
bioenergetic model


P
ω
Efficiency
Aerobic
An − lactacid
An − alactacid
P_O
P_L
P_P
bioenergetic model

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Journal of Biomechanics 34 (2001) 1077–1083

JOURNAL OF BIOMECHANICS

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www.JBiomech.com

Technical note

Predictive algorithms for neuromuscular control of human locomotion

Matthew L. Kaplan, Jean H. Heegaard*

120 J/cycle. The cost function is chosen so that at the converged solution the angular velocity of the crank is 60 rpm and the pedal angles over the crank cycle match experimental pedal angle data from Ting et al. (1999):

ature
ieuroscience

)ptimality principles in sensorimotor :ontrol

ianuel Todorov

Iost existing optimal control models[1–23] predict average movement ajectories or muscle activity, by optimizing a variety of cost func- ons. Ideally, the cost assumed in an optimal control model should orrespond to what the sensorimotor system is trying to achieve. But ow can this be quantified? A rare case where the choice of cost is

S | ONE

'e Simulation Generates Hur :ions during Loaded and Incl

Jack M. Wang[2]*, Jennifer L. Hicks[1], Scott L. Delp[1,3]

is a powerful approach for analyzing human locomotion. Unlike tech- erimental data, predictive simulations synthesize gaits by minimizing a uch as metabolic energy expenditure while satisfying task require- a target velocity. The fidelity of predictive gait simulations has only

Figure 1. Three intensity zones defined by physiological determination of the first and second ventilatory turnpoints using ventilatory equivalents for O_2 (VT_1) and CO_2 (VT_2).

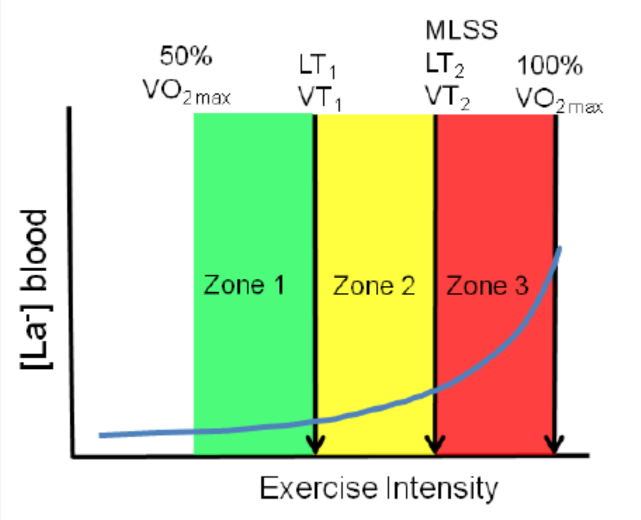


Table 1: A typical five-zone scale to prescribe and monitor training of endurance athletes.

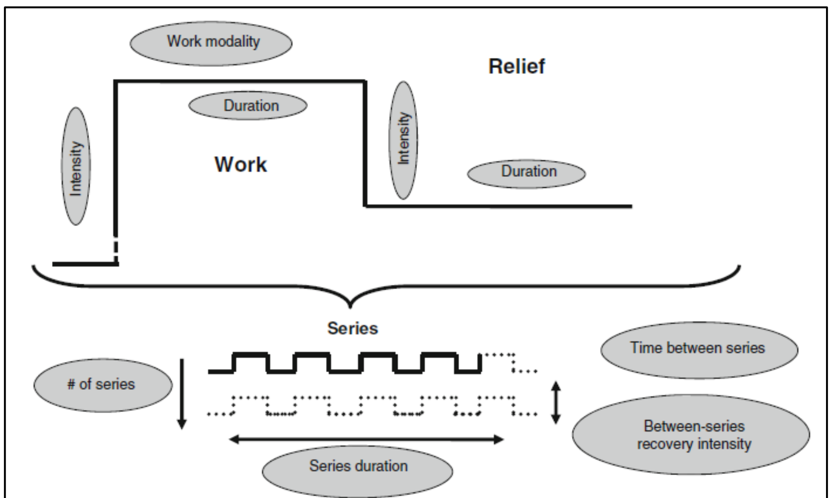
Intensity zone	VO_2 (%max)	Heart rate (%max)	Lactate (mmol.L-1)	Duration within zone
1	45-65	55-75	0.8-1.5	1-6 h
2	66-80	75-85	1.5-2.5	1-3 h
3	81-87	85-90	2.5-4	50-90 min
4	88-93	90-95	4-6	30-60 min
5	94-100	95-100	6-10	15-30 min

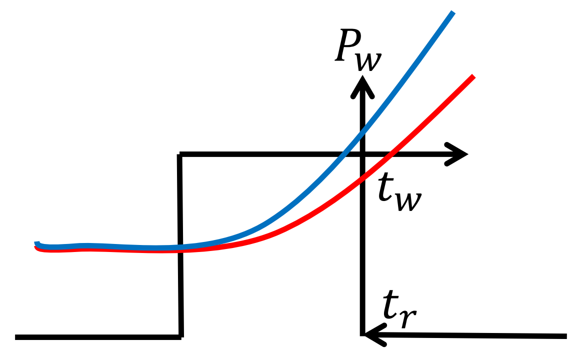
The heart rate scale is slightly simplified compared to the actual scale used by the Norwegian Olympic Federation, which is based primarily on decades of testing of cross-country skiers, biathletes, and rowers.

Table 6. Typical training sessions performed by highly trained athletes in five intensity zones (Aasen, 2008).

Zone	VO2 (%max)	Examples of training sessions	Manageable duration[a]
1	45-65	Continuous bouts	60-360 min
2	66-80	Continuous bouts	60-180 min
3	81-87	6 x 15 min, 2-min rec 2 x 25 min, 3-min rec 5 x 10 min, 2-min rec 8 x 8 min, 2-min rec LT 40-60 min 50 x 1 min, 20-s rec	50-90 min
4	88-93	10 x 6 min, 2-3-min rec 8 x 5 min, 3-min rec 15 x 3 min, 1-min rec 40 x 1 min, 30-s rec 10 x (5 x 40 s, 20-s rec), 2- to 3-min breaks 30-40 min steady state	30-60 min
5	94-100	6 x 5 min, 3-4-min rec 6 x 4 min, 4-min rec 8 x 3 min, 2-min rec 5 x (5 x 1 min, 30-s rec), 2- to 3-min breaks	24-30 min

[a] Warm-up and rest periods in interval bouts are not included.
LT, lactate threshold (max steady state); rec, recoveries.



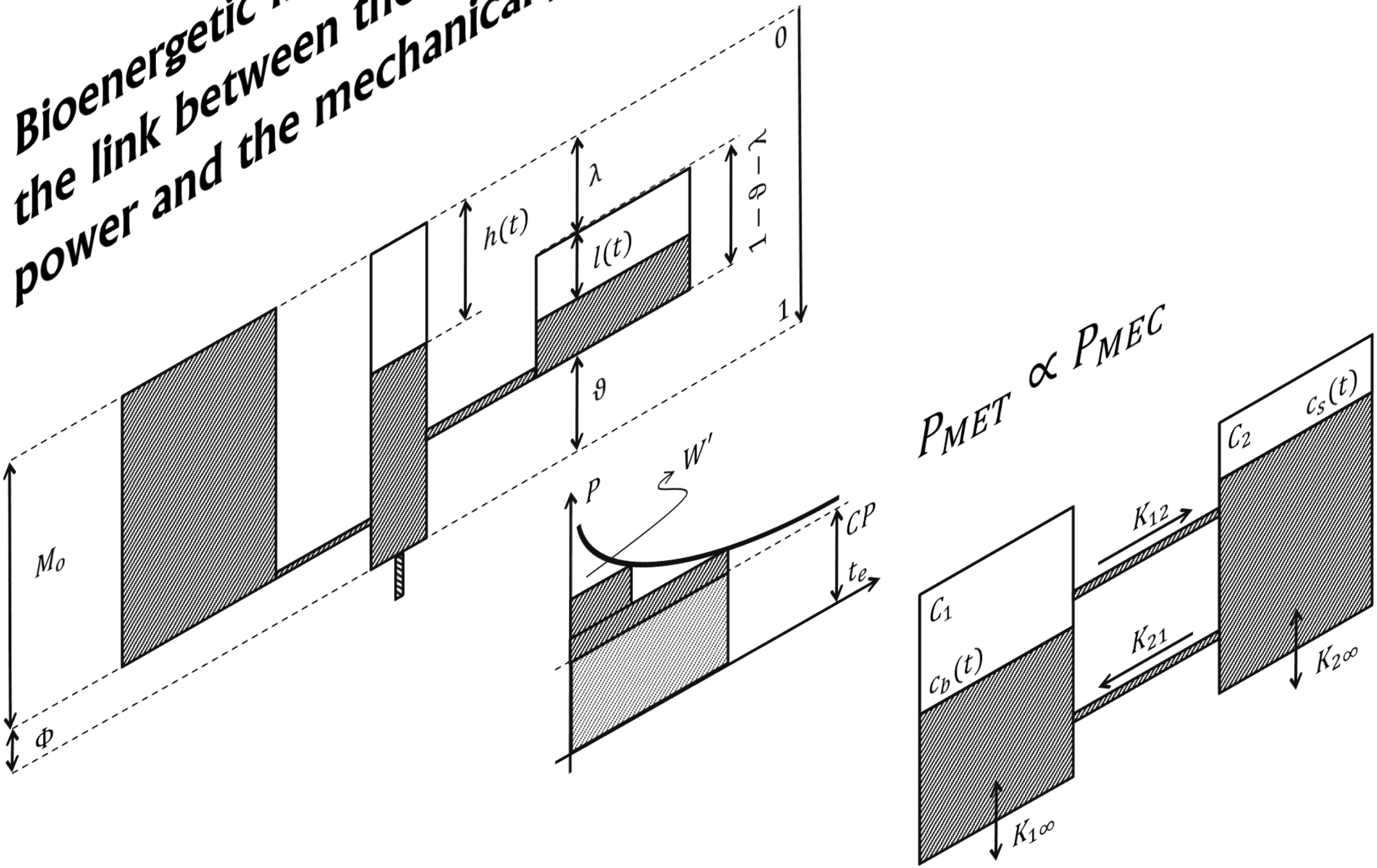


"What if" scenarios and sensitivity

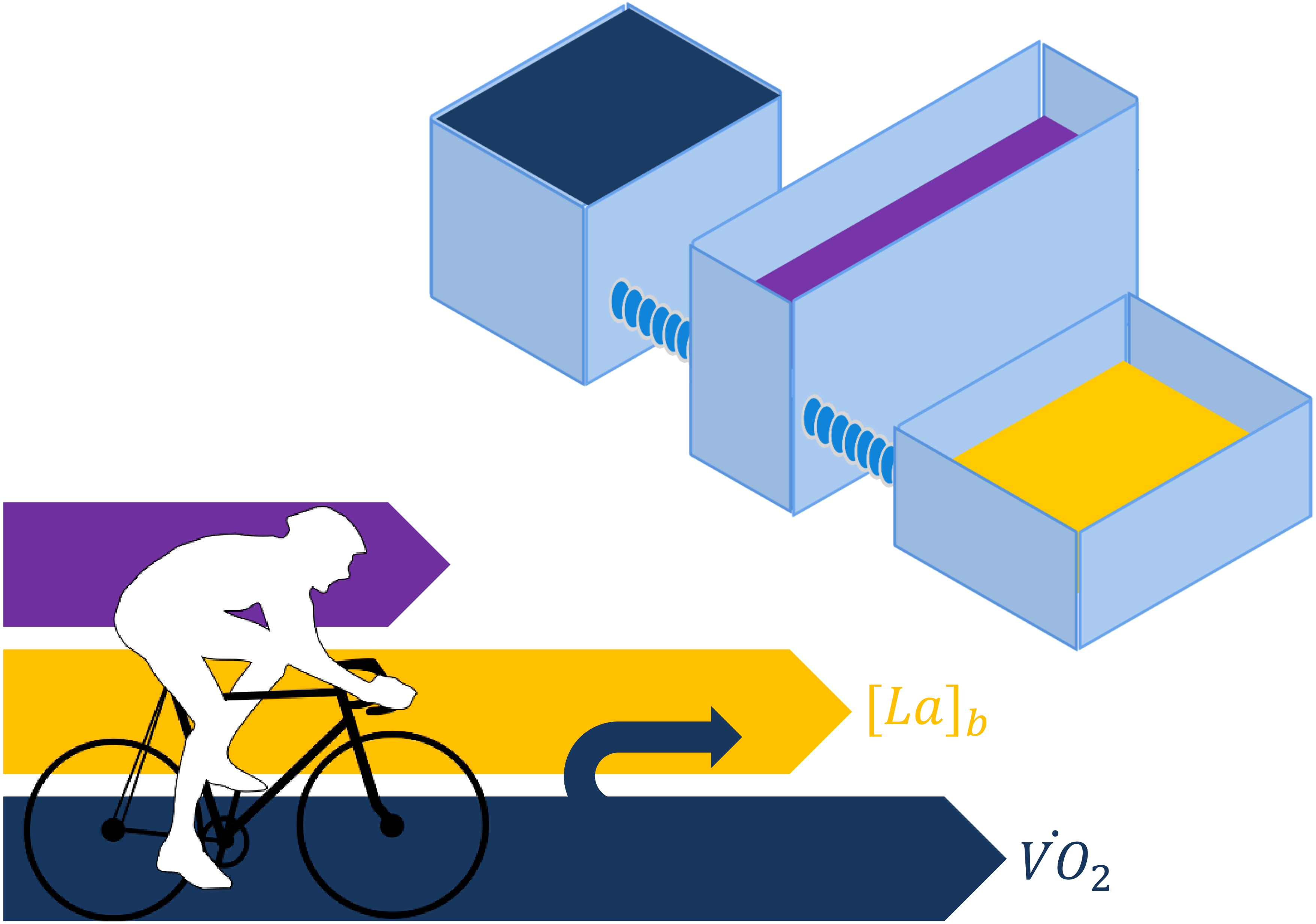
Seiler, *What is best practice for training intensity and duration distribution in endurance athletes, Int J Sports Physiol Perform* 2010

Buchheit and Laursen, *HIT Solutions to the Programming Puzzle, Sport Science, 2013*

Bioenergetic models: the link between the metabolic power and the mechanical power

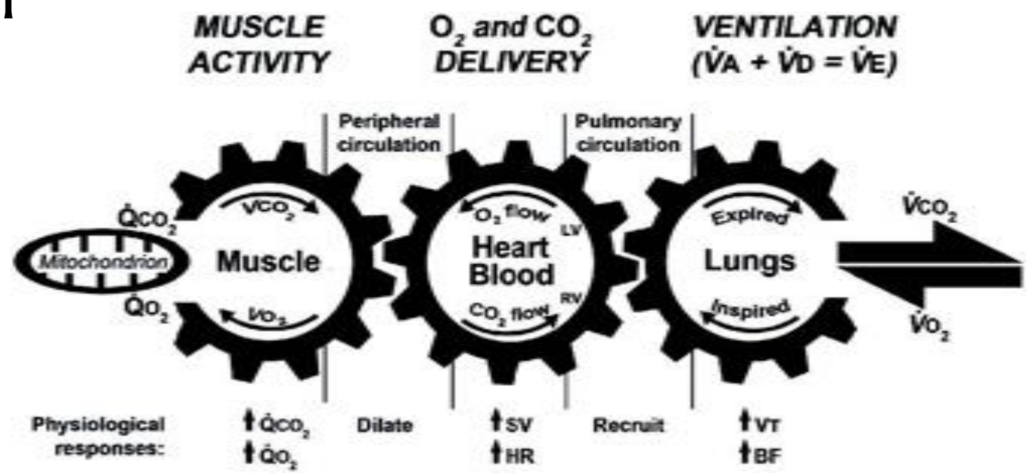


$P_{MET} \propto P_{MEC}$



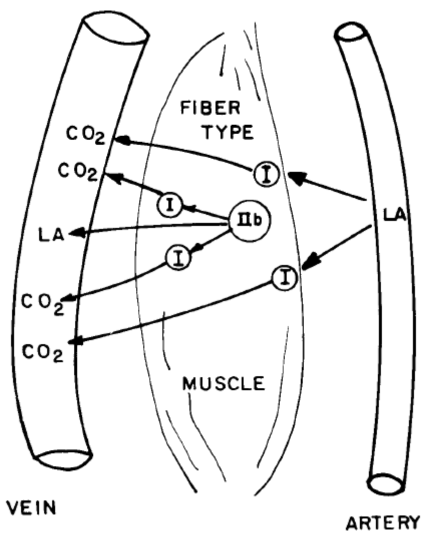
Morton, *A three component model of human bioenergetics, J of math bio,* 1986

The lack of oxygen is the trigger for the lactate production and the lactate produced during exercise is a dead-end metabolite that can only be removed during recovery

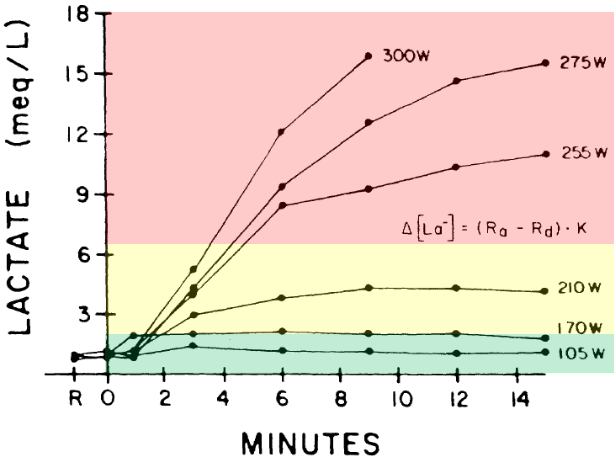


Wasserman, *Determinants and detection of anaerobic threshold, Circulation*, 1987

Lactate plays a key role in the distribution of the carbohydrate potential energy and lactate is produced in fully oxygenated muscles



Brooks, *Intra and extra cellular lactate shuttle, MSSE*, 2000



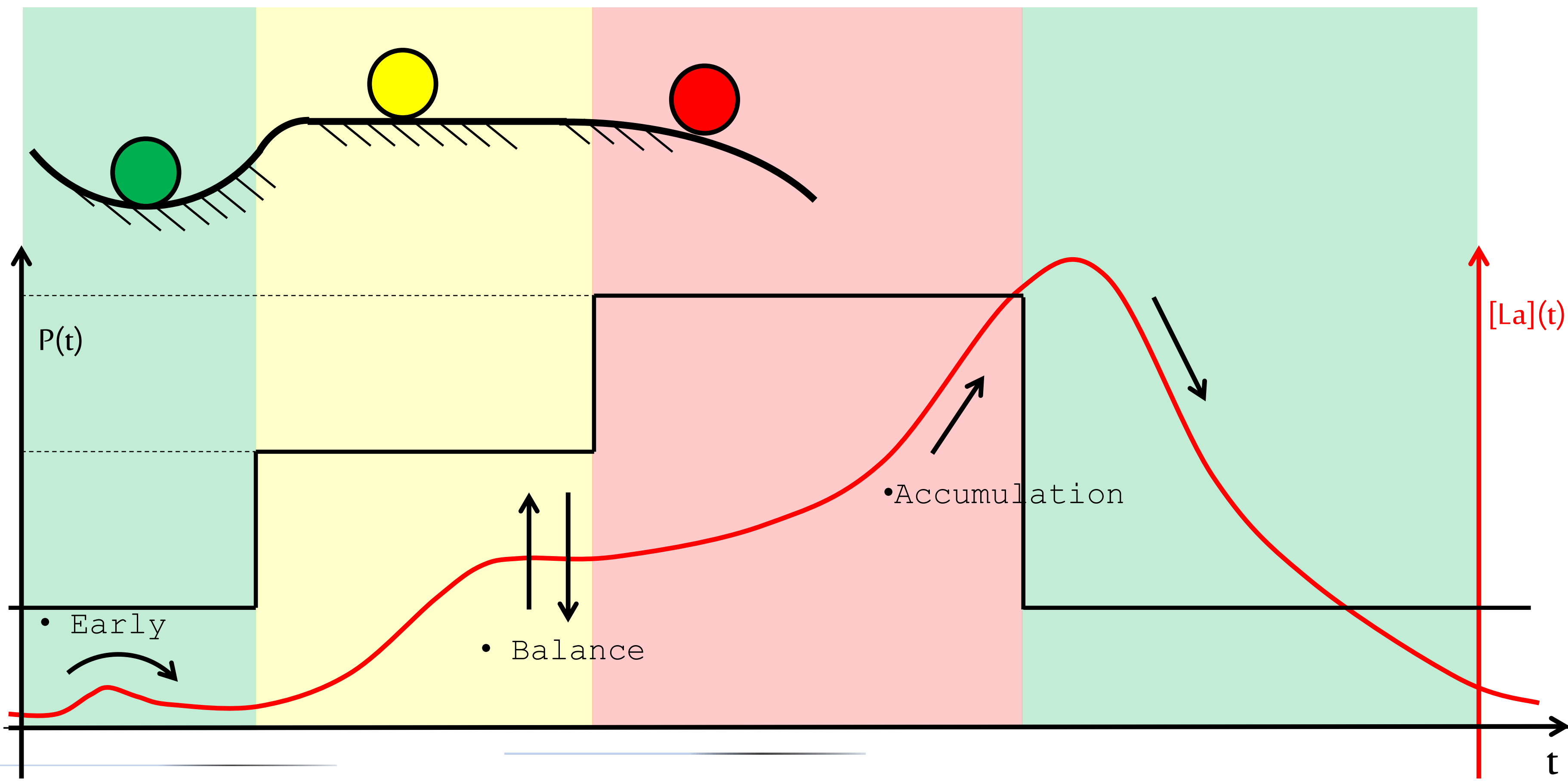
Characteristics of the lactate dynamics

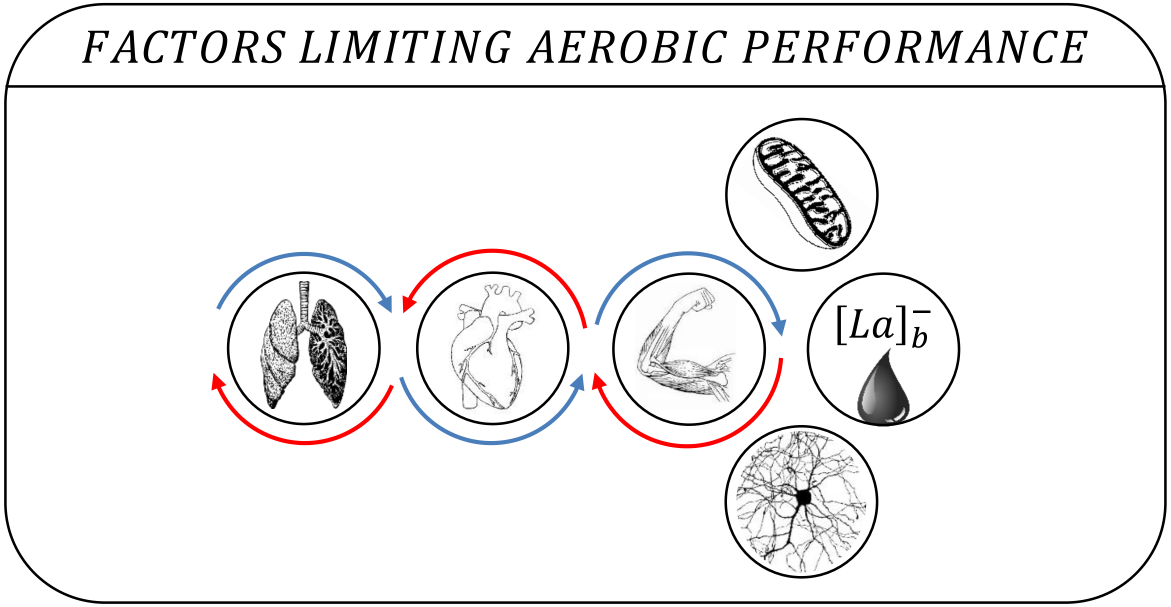
Early lactate (moderate)

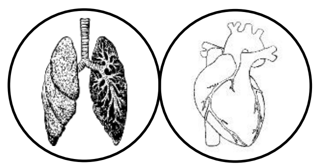
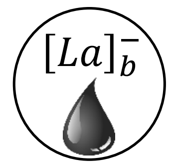
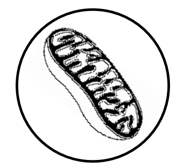
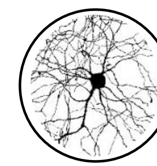
Balance below MLSS (heavy)

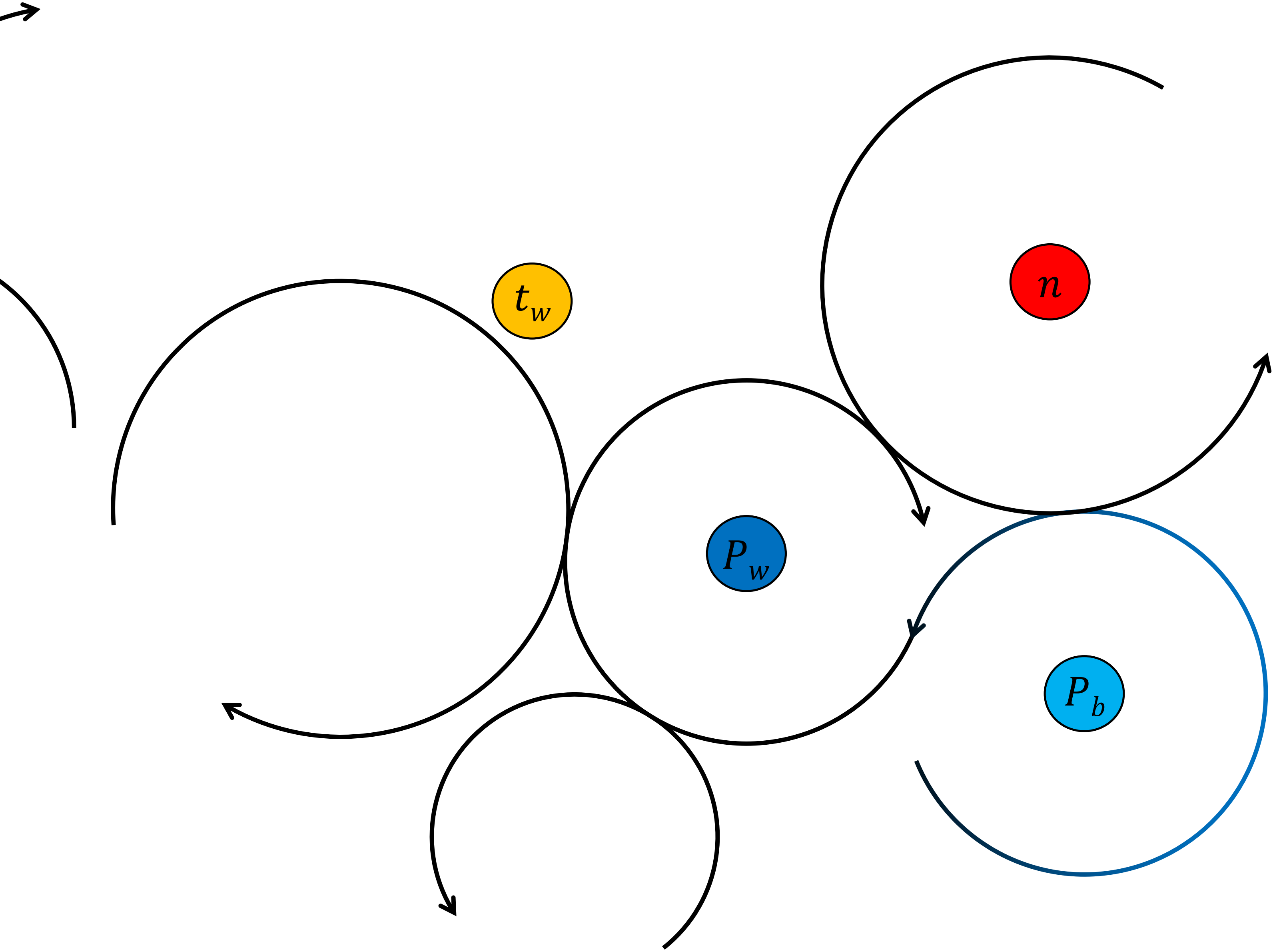
Accumulation (severe)

Delayed peak

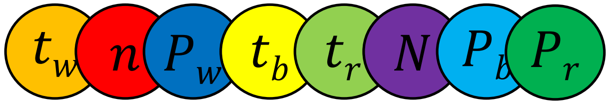




e.g. training protocol		 		
n×(30’’:30’’)@(100%:0)	+++	+		
n×(2’:2’’)@(100%:0)	+	+++		
n×(30’’:5’30’’)@(150%:0)		+++		
n×(6’:6’)@(90%:0)	++		++	



t_w
n
P_w
P_b


t_w
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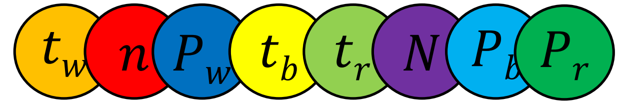
t_r
N
P_b
P_r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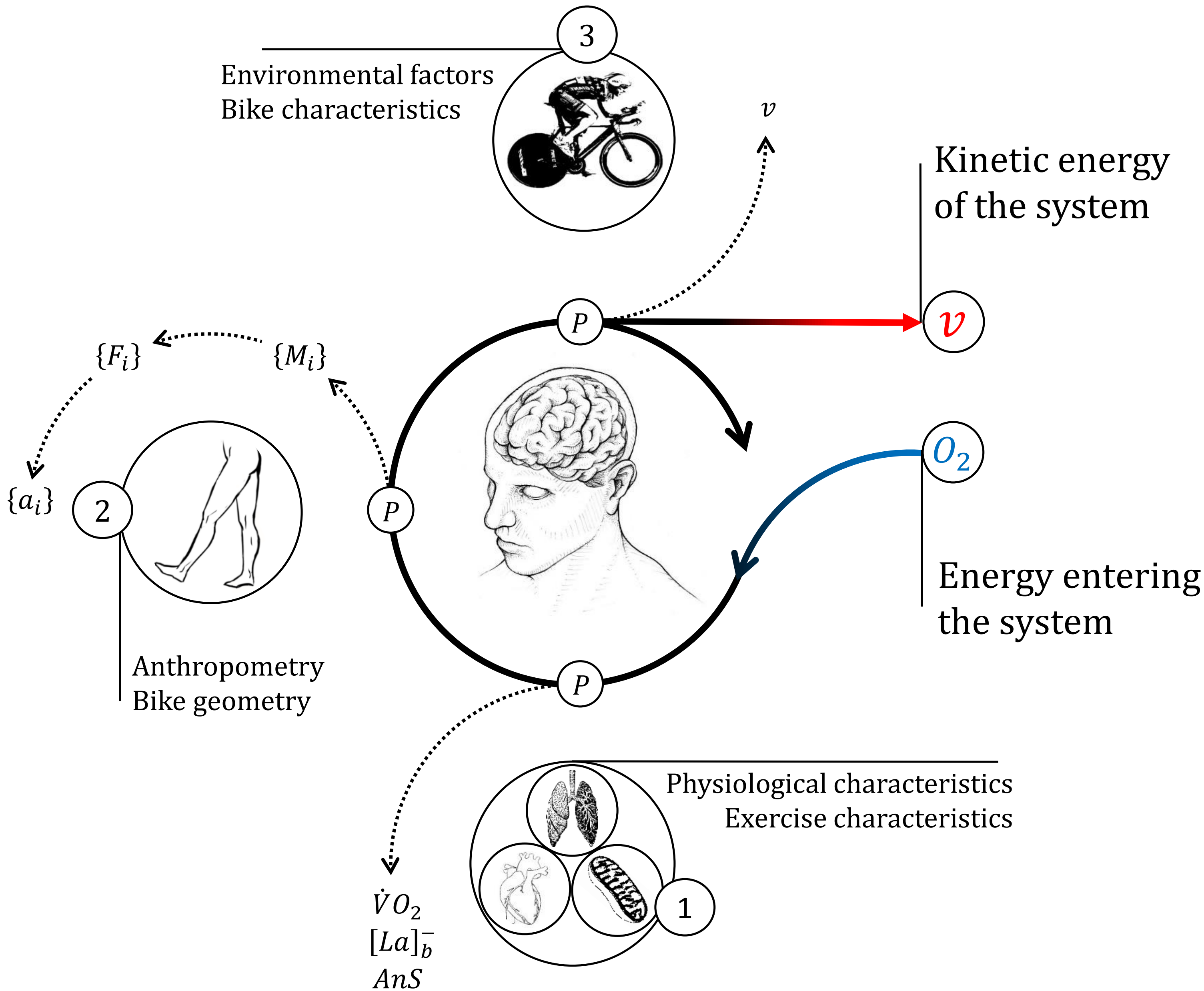
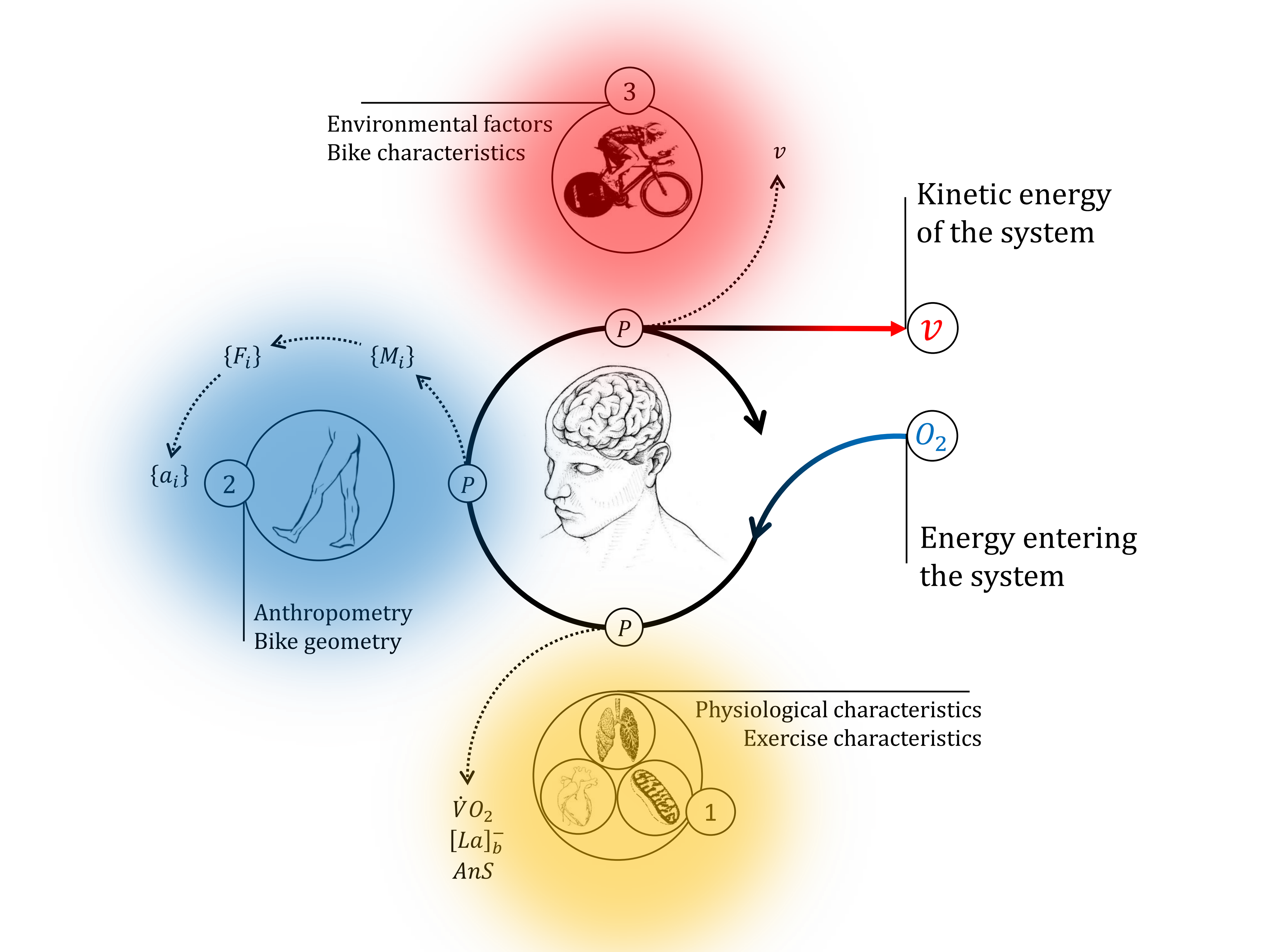

3
Environmental factors
Bike characteristics
v
Kinetic energy
of the system
P
v
{F_i}
{M_i}
{a_i}
2
P
O_2
Energy entering
the system
Anthropometry
Bike geometry
P
Physiological characteristics
Exercise characteristics
$\dot{V}O_2$
$[La]_b^-$
AnS
1

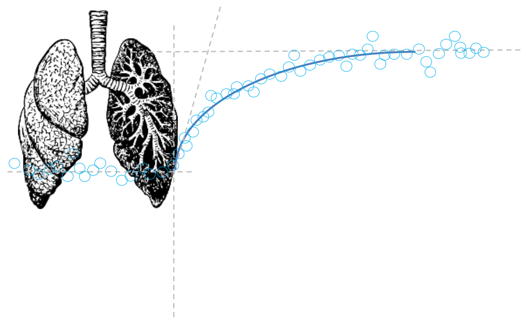


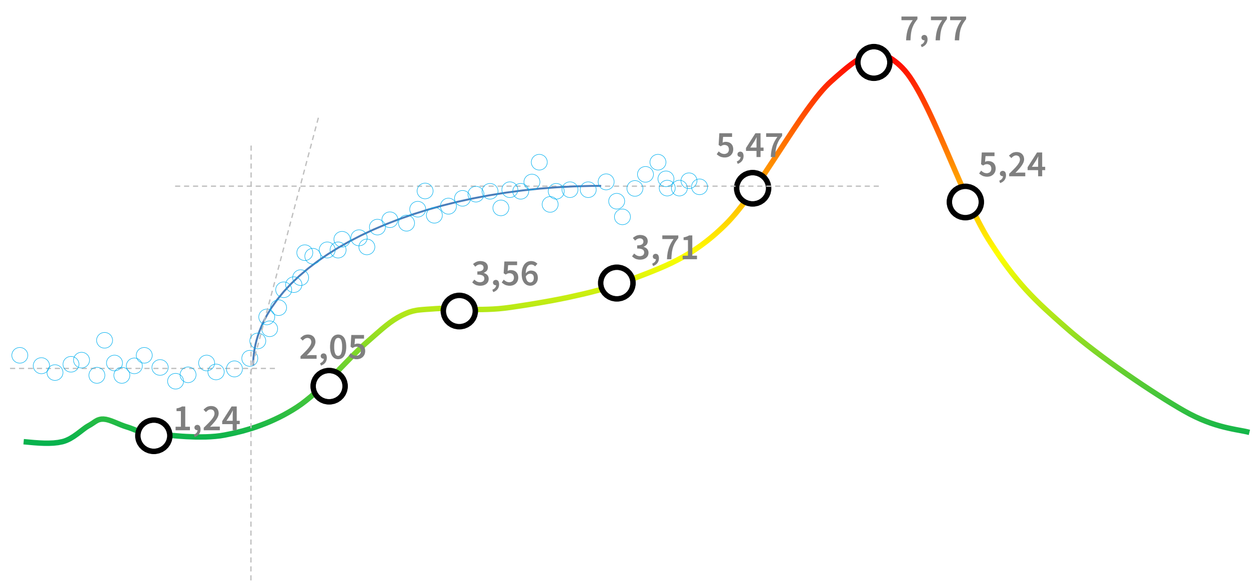
3
Environmental factors
Bike characteristics
v
Kinetic energy of the system
P
v
$\{F_i\}$
$\{M_i\}$
$\{a_i\}$
2
P
O_2
Energy entering the system
Anthropometry
Bike geometry
P
Physiological characteristics
Exercise characteristics
$\dot{V}O_2$
$[La]_b^-$
AnS
1

1

3

2





Outline of the today's presentation

1

Bioenergetic models

The link between the mechanical power and metabolic power

$1a$ HIT: an optimal control solution to the programming puzzle

2

Mechanical models

The link between the mechanical power and the joint torques

$2a$ Predictive dynamics of a constrained movement

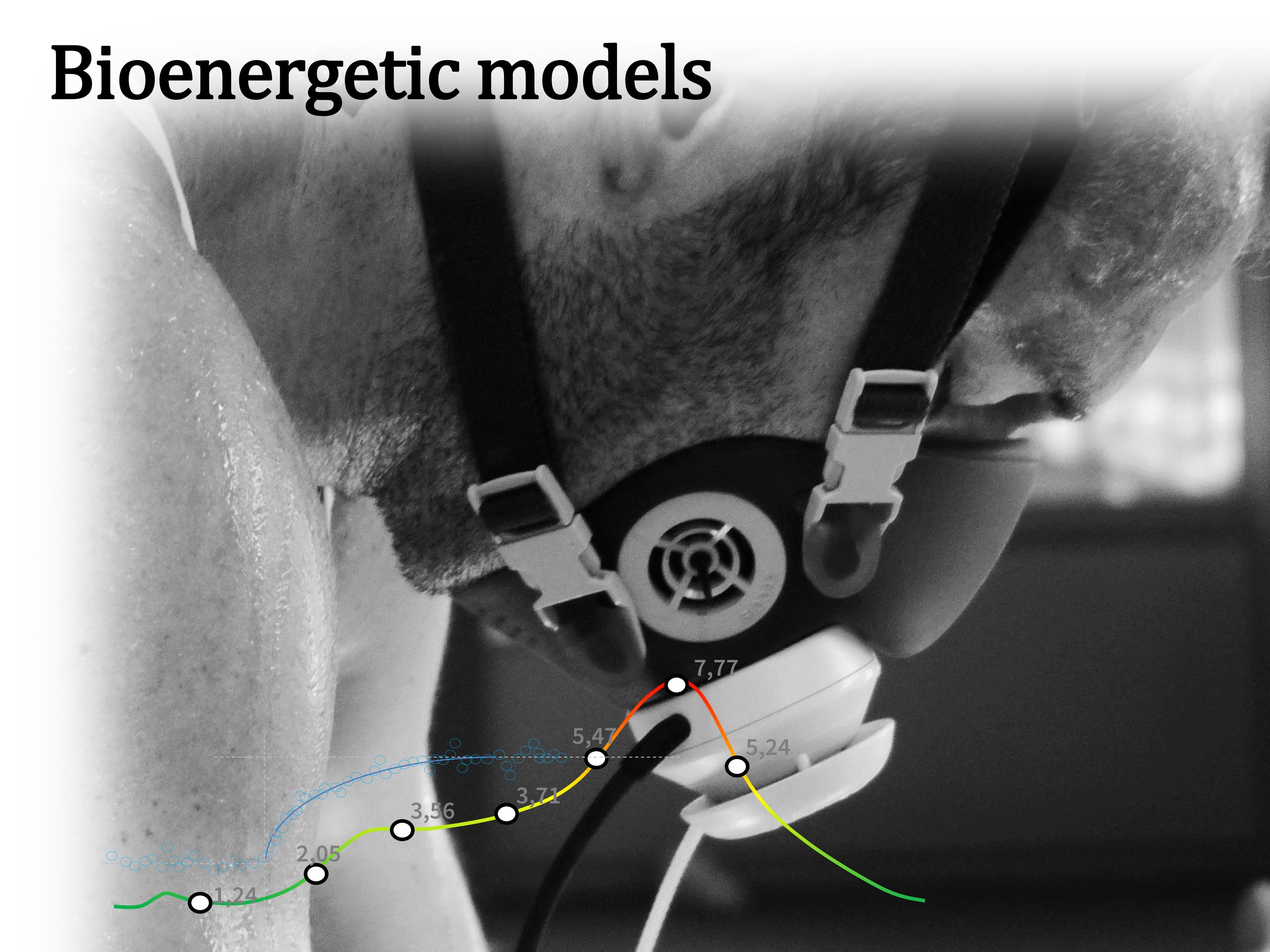
3

Locomotion models

The link between the mechanical power and the speed

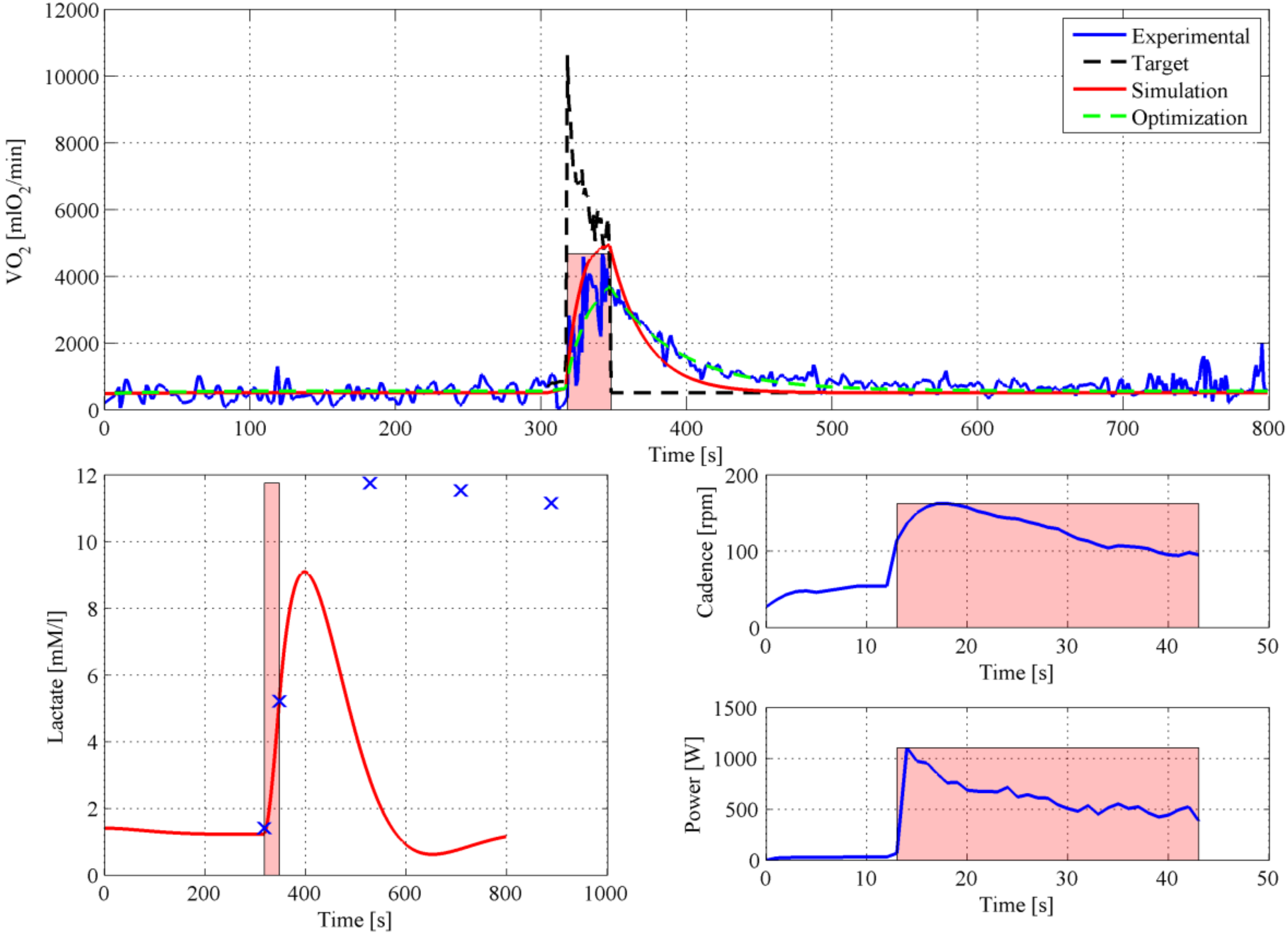
$3a$ Optimal control solution to pacing strategy

Bioenergetic models

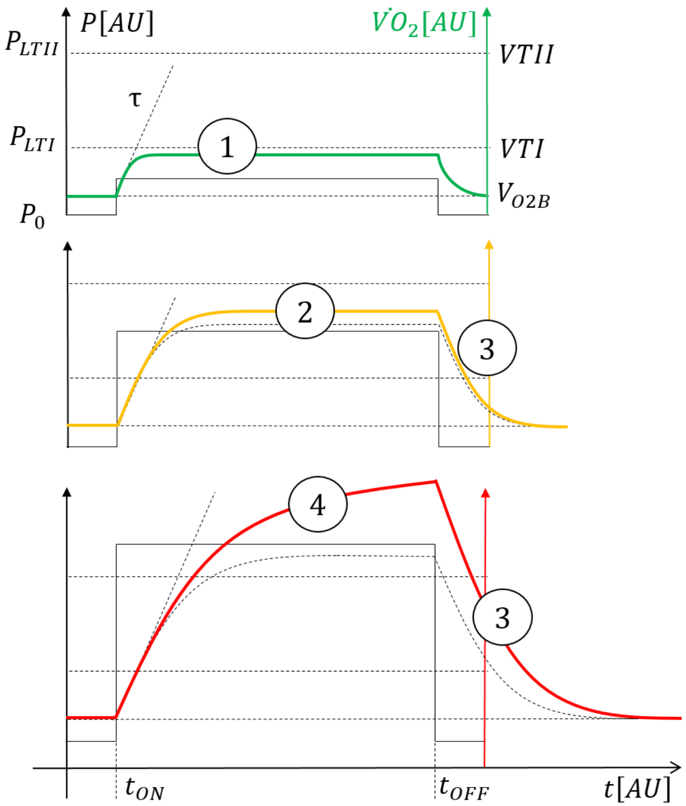


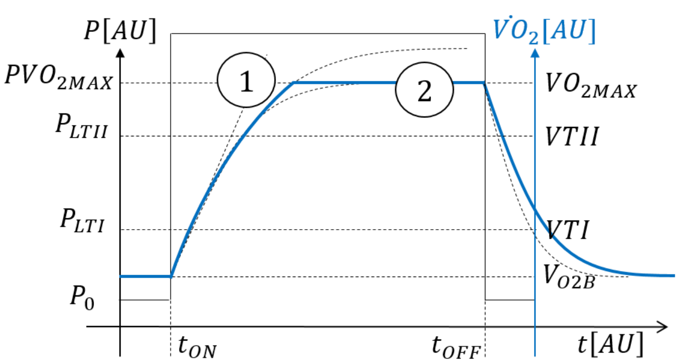
30s Wingate test

$$[La](t) = [La](0) + A_1(1 - e^{-\gamma_1 t}) + A_2(1 - e^{-\gamma_2 t})$$



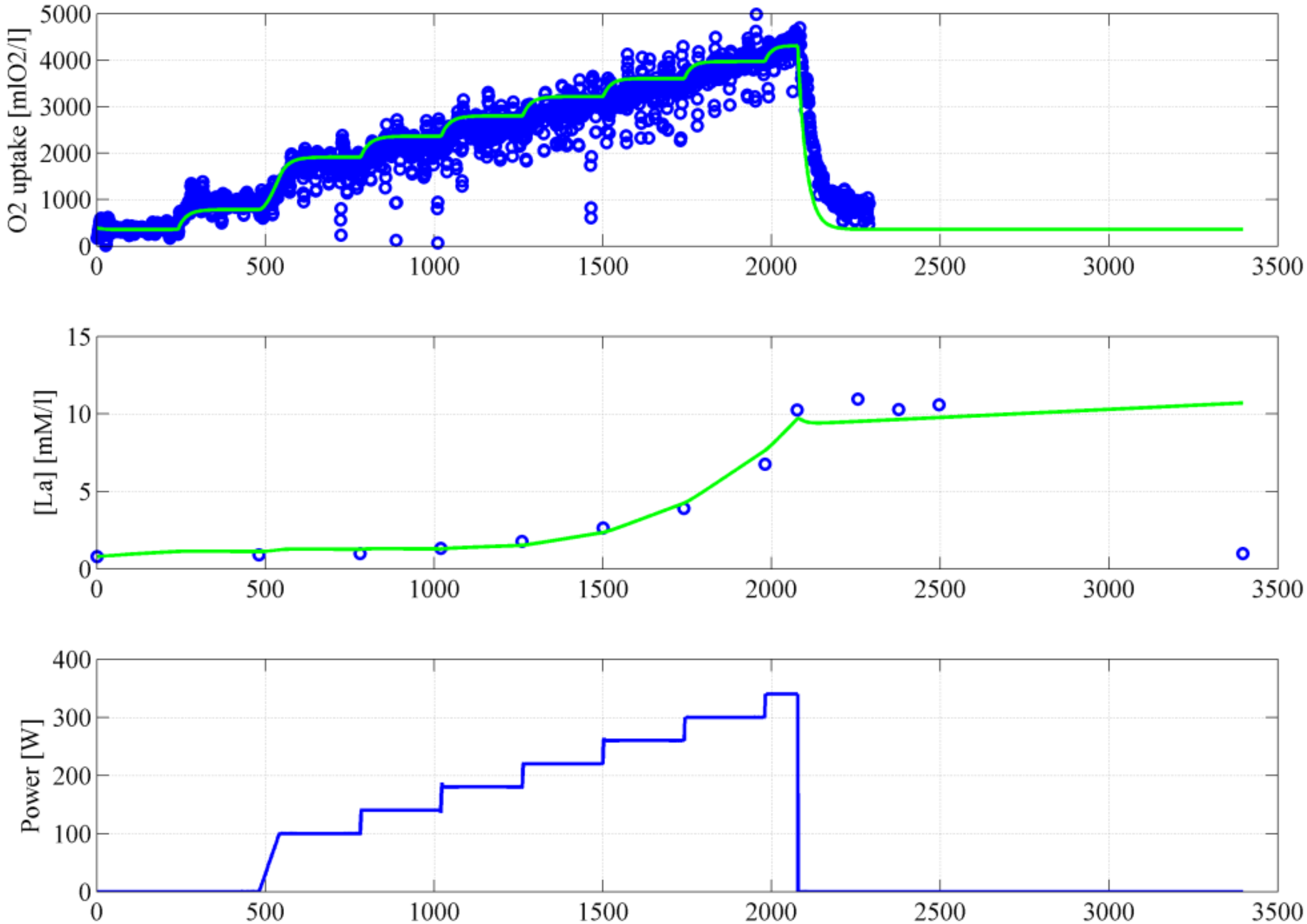
Freund and Gendry, *Lactate kinetics after short strenuous exercise in man*, *EJAP*, 1978


$P[AU]$
$\dot{V}O_2[AU]$
P_{LTII}
$VTII$
τ
P_{LTI}
1
VTI
V_{O2B}
P_0
2
3
4
3
t_{ON}
t_{OFF}
$t[AU]$


$P[AU]$
$\dot{V}O_2[AU]$
PVO_{2MAX}
1
2
VO_{2MAX}
P_{LTII}
$VTII$
P_{LTI}
VTI
P_0
V_{O2B}
t_{ON}
t_{OFF}
$t[AU]$

Custom written models in incremental to exhaustion

$$[\dot{La}] = p_0\left(\dot{V}O_2(t) - \frac{\alpha_0}{\beta_0 p_0}\tanh(\beta_0 p_0 \dot{V}O_2(t))\right) - d_0\left(\tanh\left(\frac{[La](t)\chi}{\chi}\right)\right)\cdot D\left(\dot{V}O_2(t) - \frac{\alpha_0}{\beta_0 p_0}\tanh(\beta_0 p_0 \dot{V}O_{2ss})\right)\cdot\left(\dot{V}O_{2MAX} - \dot{V}O_2(t)\right)$$



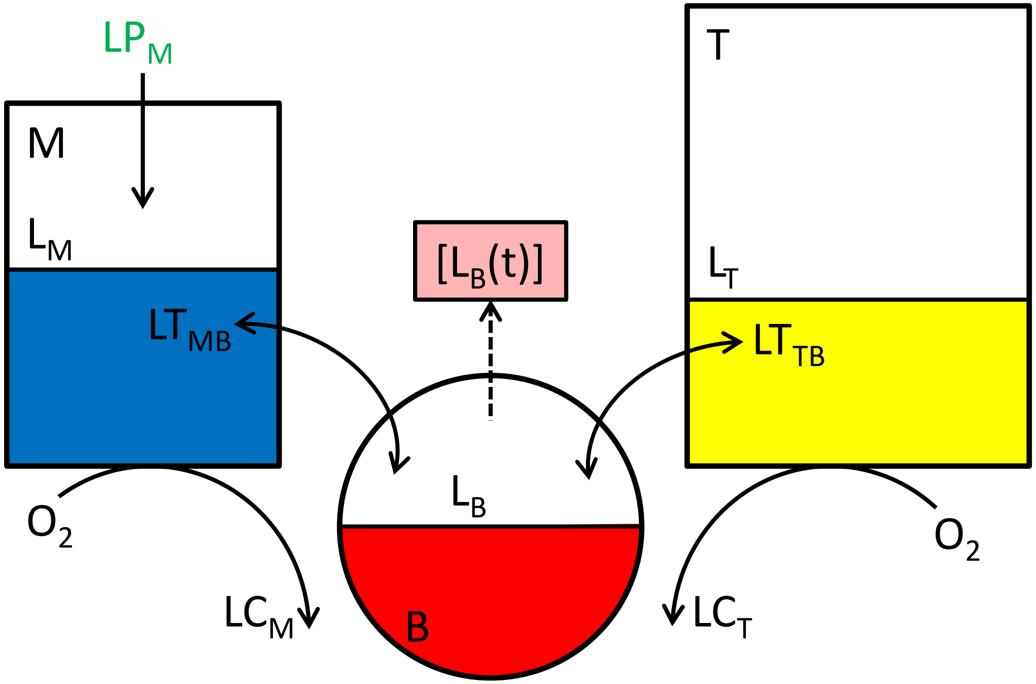
Moxnes and Sandbakk, *The kinetics of lactate production and removal during whole body exercise*, *Theor Bio Med Mod*, 2012

Gradient driven lactate transfer
Lactate is produced and cleared in muscles and tissues

$$\Delta L_B = K_T(L_B - L_T) + K_M(L_B - L_M)$$

$$\Delta L_T = K_{T0}(L_T) + K_T(L_T - L_B)$$

$$\Delta L_M = K_{M0}(L_M) + K_M(L_M - L_B) + LP_M$$

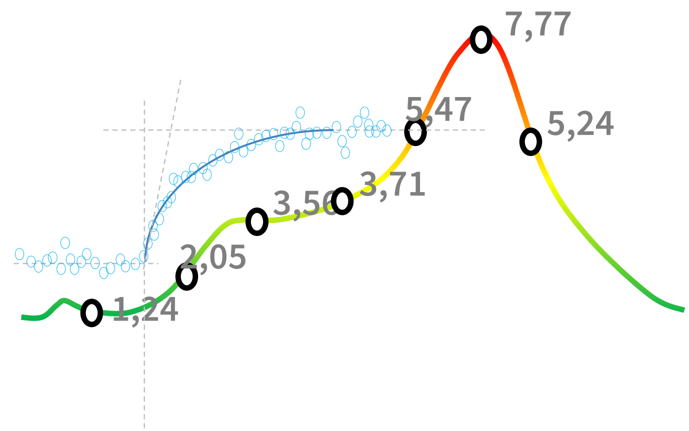


Take-home messages

Validating models with experimental data and extending what is known at the theoretical level to the real world practice, testing ideas and stimulating new research questions.

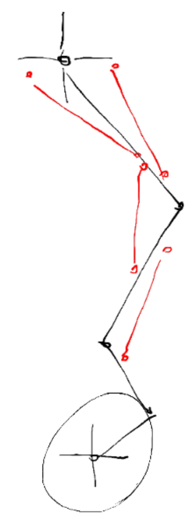
Bioenergetics:

1. fatigue free models until you do not specify how the model parameters are affected by the fatigue.
2. Accuracy is increased in the lactate concentration dynamics if a control for the metabolic pathway is included (metabolic control seems not to be a passive response).



Biomechanics:

1. static and dynamic optimization for the solution of the inverse dynamic is practically equivalent for slow movements (e.g. walking gait) but the difference drifts away for faster movements (in which also data acquisition is more difficult).
2. Optimization on torques hides the muscle functions

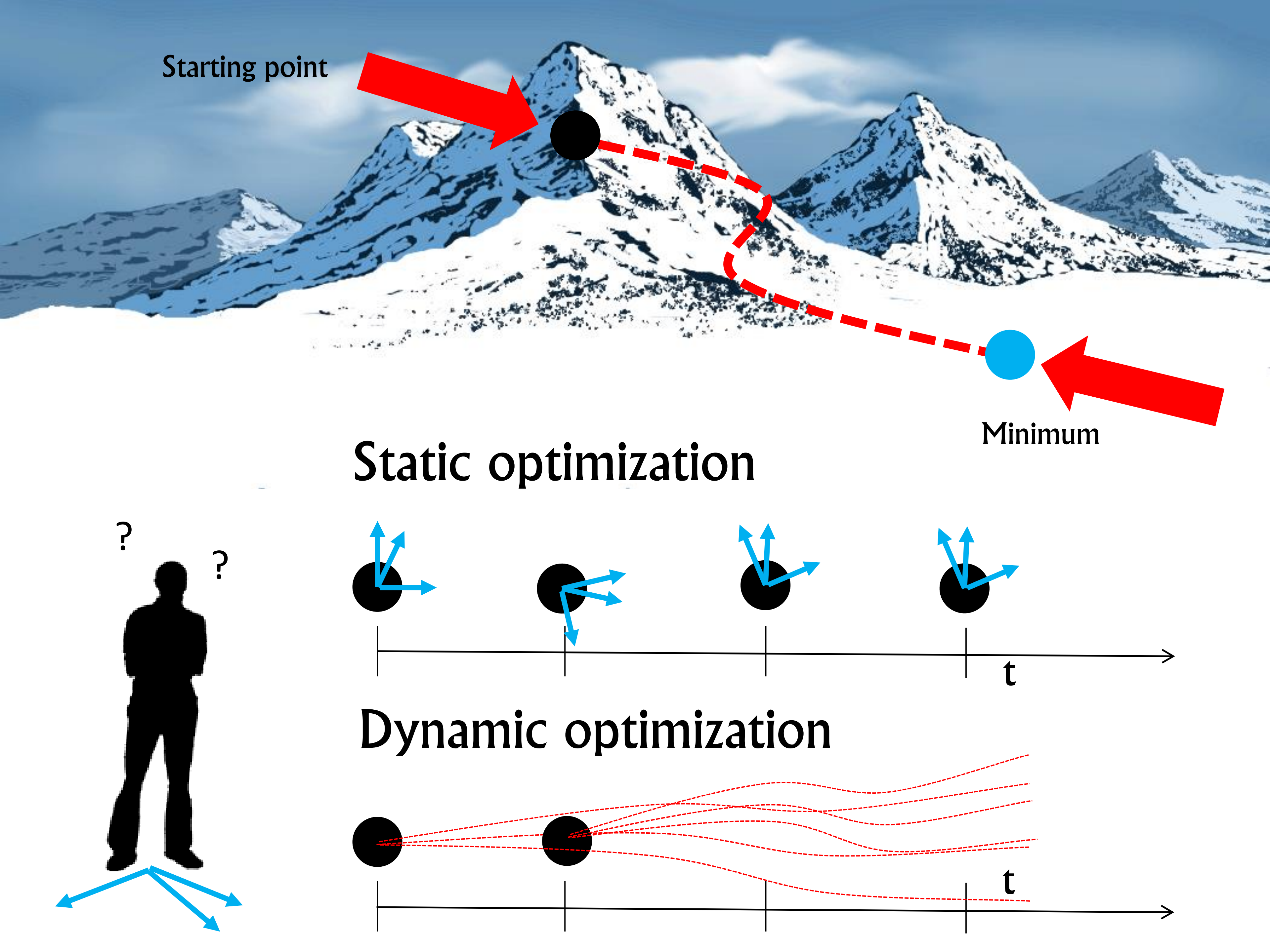


$Y = f(x,u,t)$

$PHI(t) = 0$

$\{B\} > 0$

$\{C\} = 0$

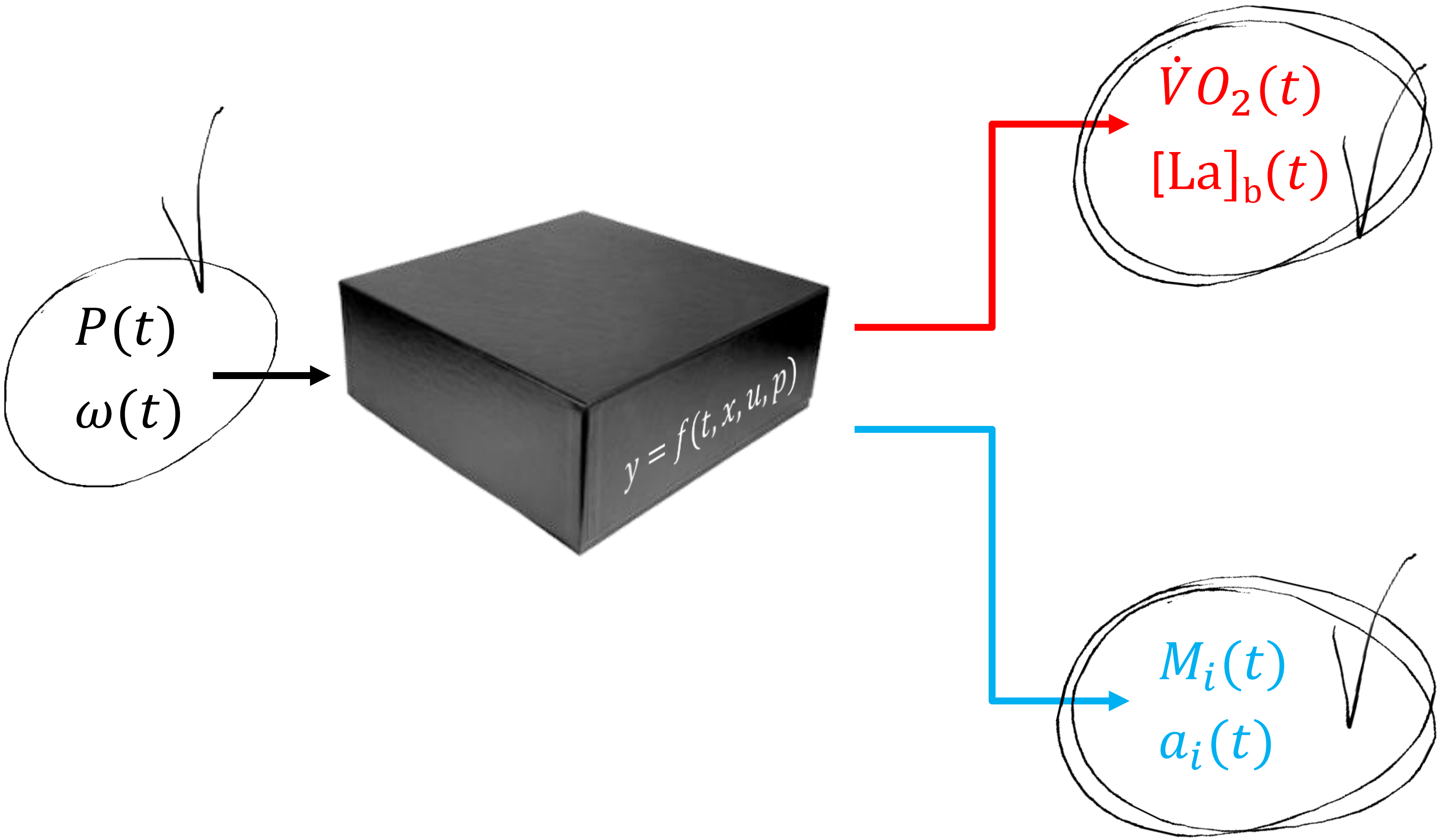

Starting point
Minimum
Static optimization
?
?
t
Dynamic optimization
t

Fact: On July 17th 2013 Chris Froome bested Alberto Contador of 9 seconds in TT Embrun. He switched during the course from a Pinarello Dogma 65.1 to Bolide TT bike. He was 11 seconds down and he spent 15 seconds in the bike switch. He finished 10 seconds faster.

Question: can we know if switching the bike can lead to a better overall performance?

Fact: On June 7^{th} 2015 Bradley Wiggins cycled 54.526 kilometers in a hour.

Question: can we predict the average power provided?


$P(t)$
$\omega(t)$
$y = f(t, x, u, p)$
$\dot{V}O_2(t)$
$[\mathrm{La}]_\mathrm{b}(t)$
$M_i(t)$
$a_i(t)$