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MECHATRONIC SYSTEM MODELLING
MECHATRONICS RESEARCH GROUP
UNIVERSITY OF TRENTO - Italy

What virtual modeling can tell us about bioenergetics and biomechanics of cycling

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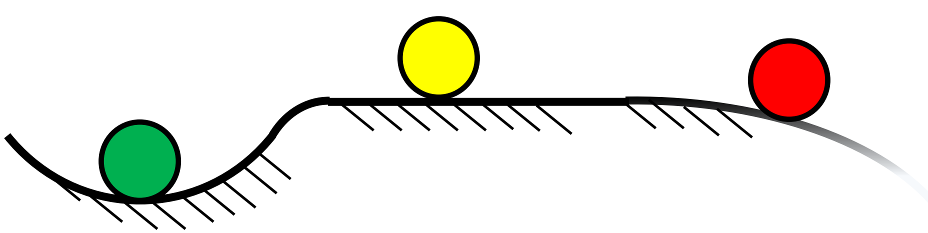


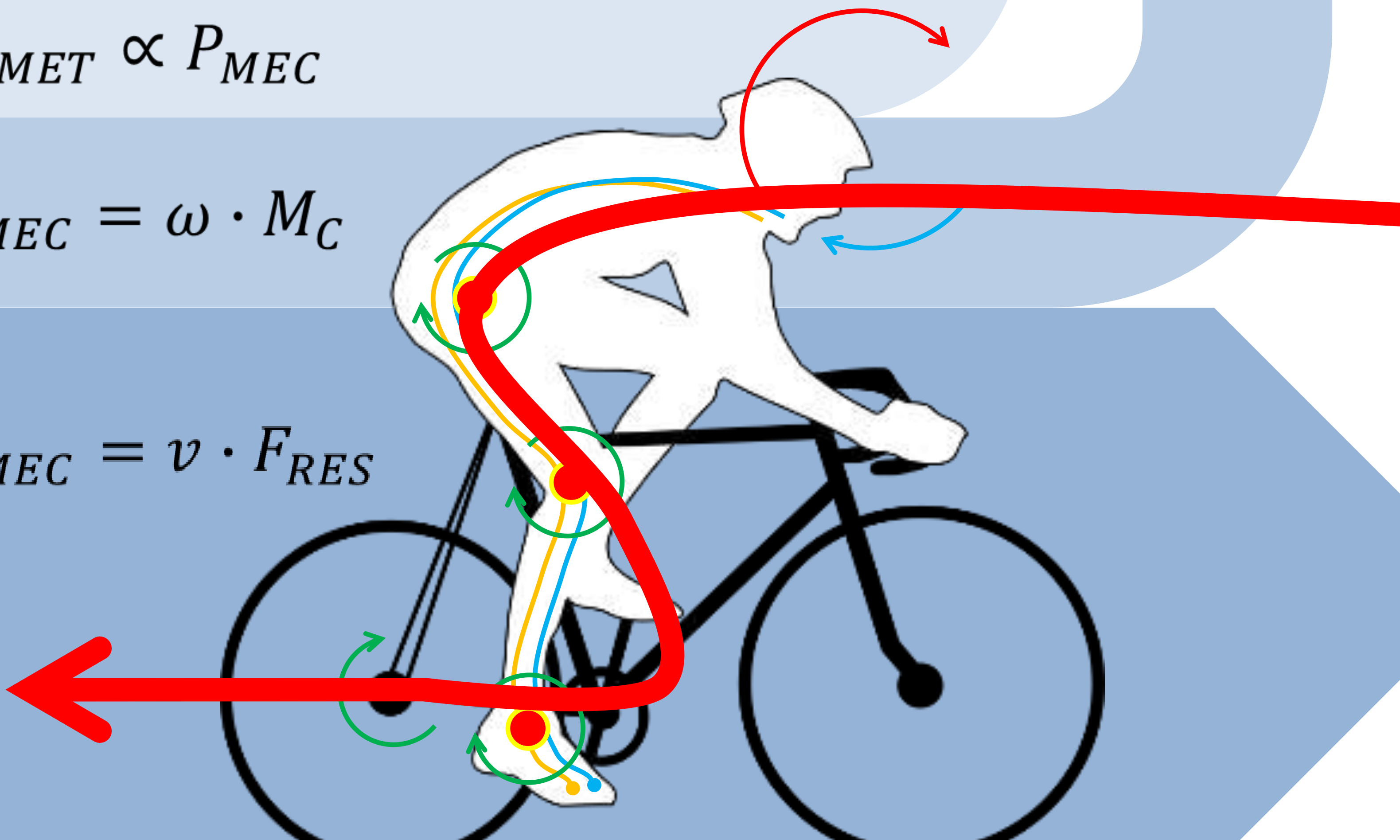
MSH Congress,
Rovereto, Trento,
Friday November 13th, 2015

Different levels of analysis

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

$$P_{MEC} = \omega \cdot M_C$$

$$P_{MEC} = v \cdot F_{RES}$$

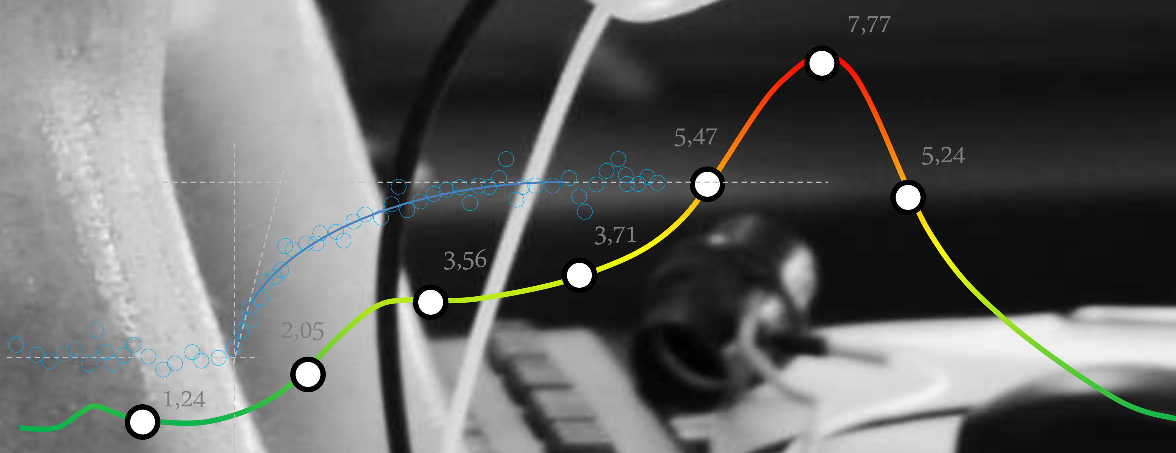


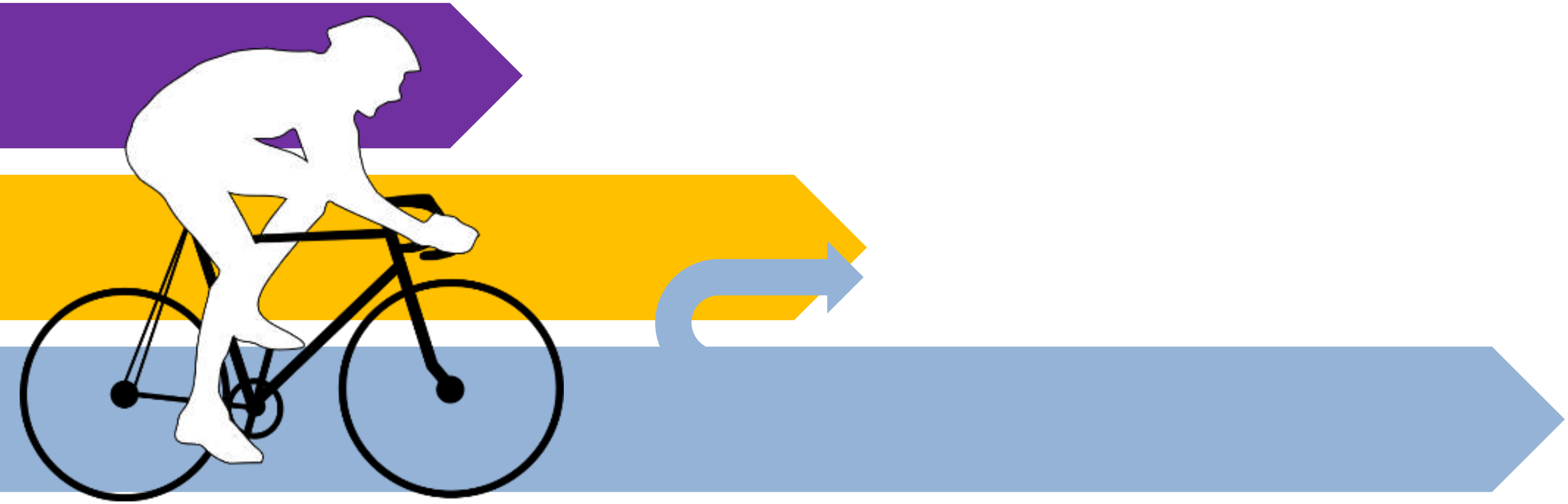
OUTLINE:

- Bioenergetic models:
  - Metabolic pathways and how to model them
  - Focus: lactate concentration
- Biomechanical models:
  - The problem of abundance and how to solve it
  - Focus: optimal control for the inverse dynamic
- Concluding remarks
  - Take home messages

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

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





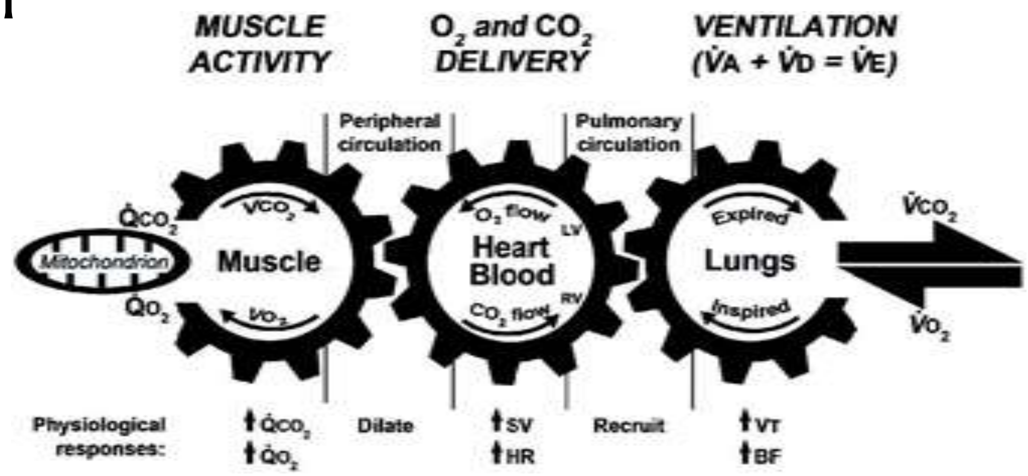
$\dot{V}O_2$

The pulmonary **oxygen** consumption that we are collecting in the laboratory can be used as proxy for the total oxygen used in aerobic processes

$[La]_b$

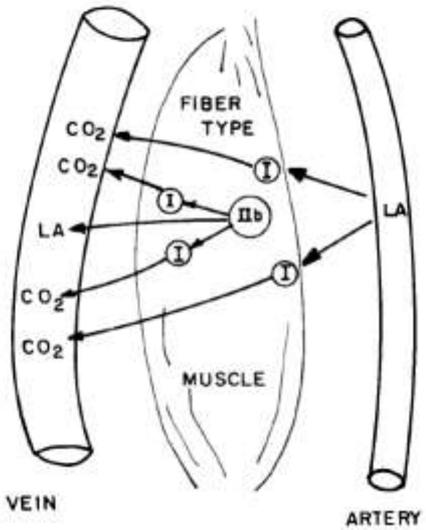
The blood **lactate** concentration that we are collecting in the laboratory can be used as proxy for the blood lactate concentration

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

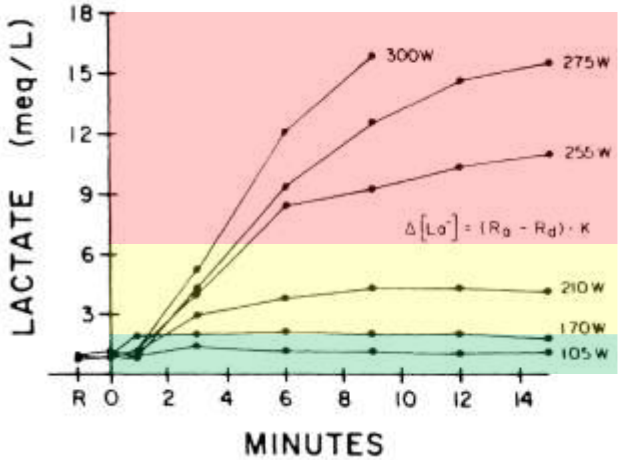


Wasserman, *Determinants and detection of anaerobic threshold, Circulation*, 1987

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

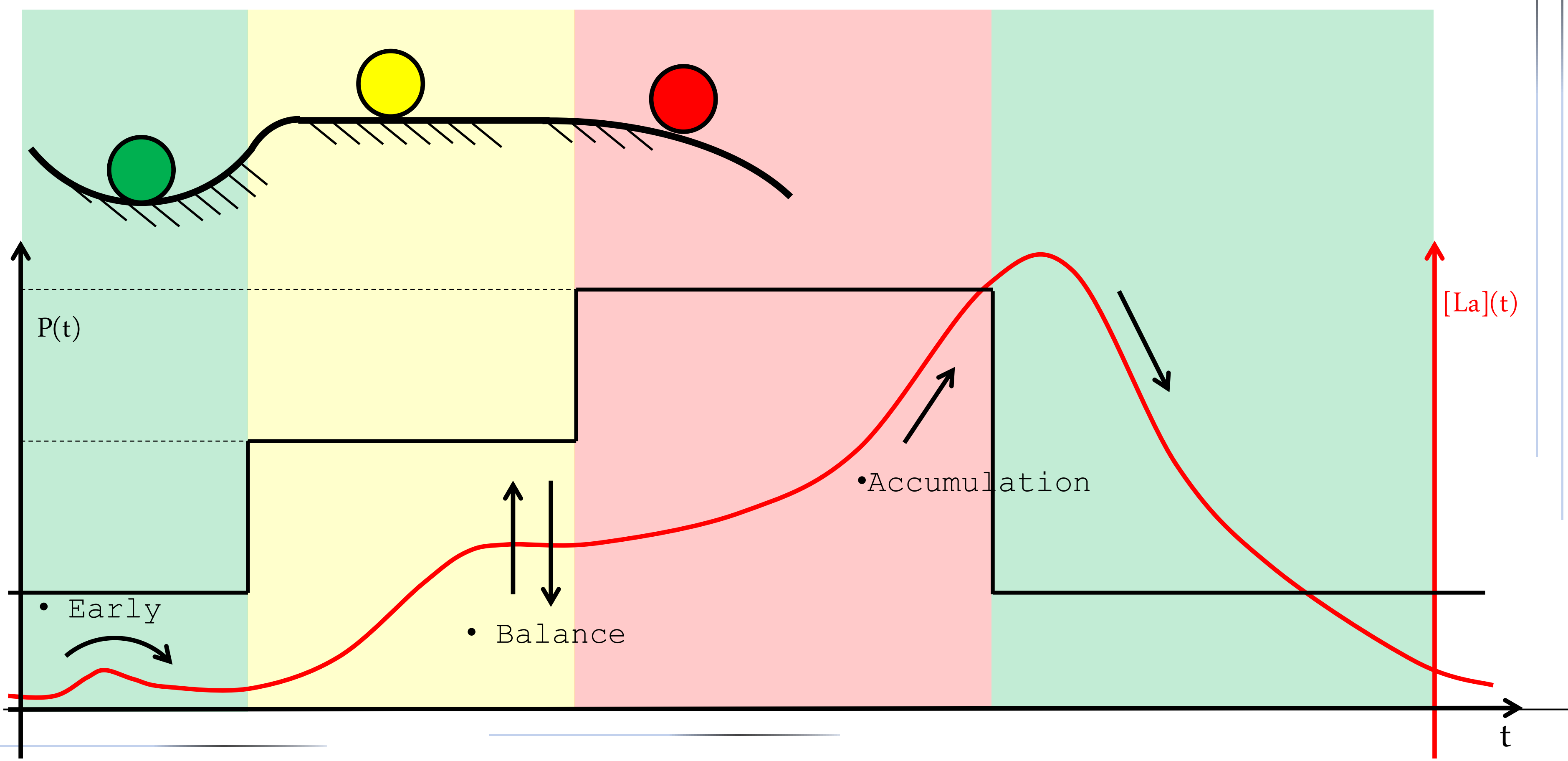


Brooks, *Intra and extra cellular lactate shuttle, MSSE*, 2000



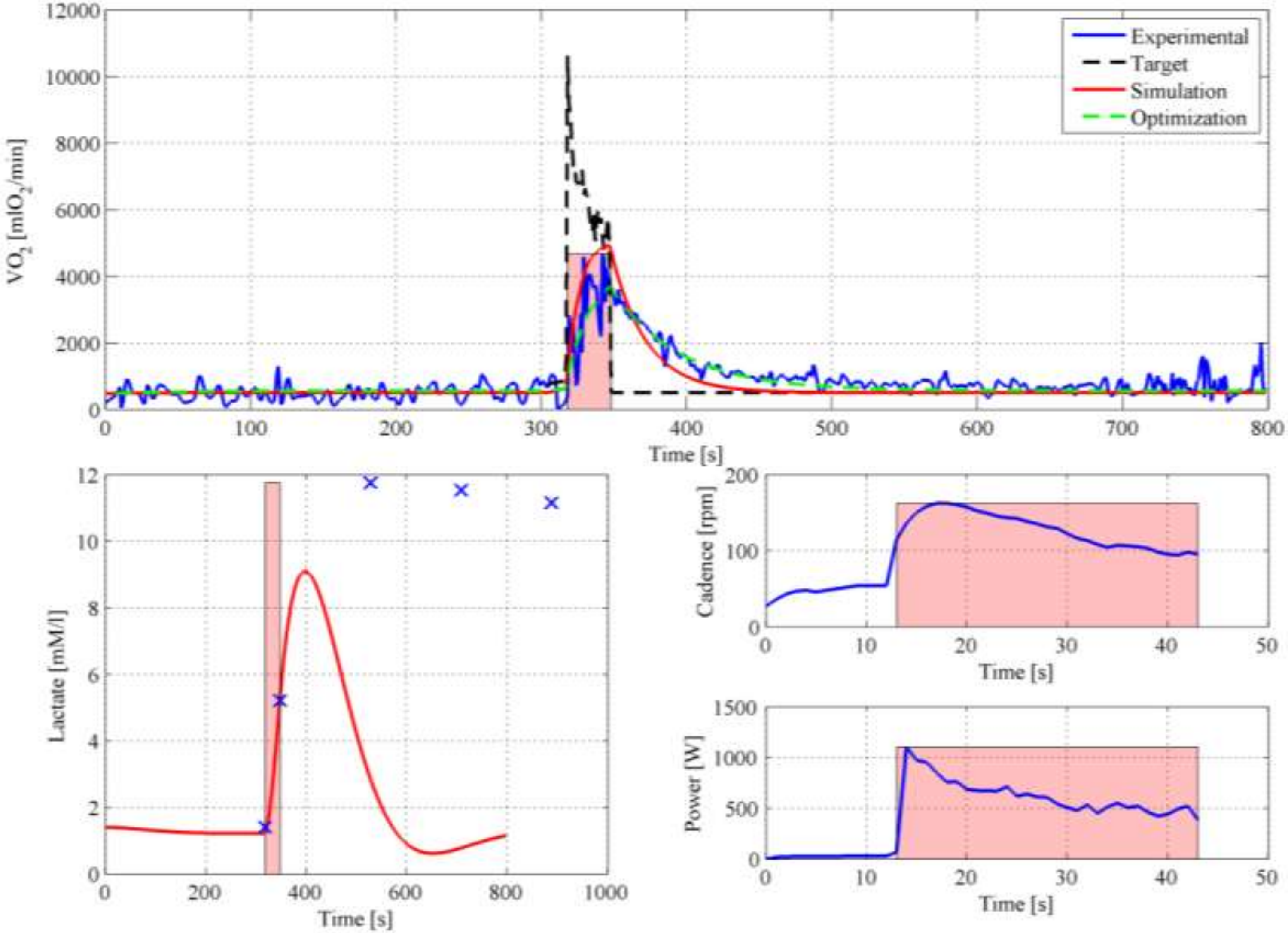
Characteristics of the lactate dynamics

Early lactate (moderate)
Balance below MLSS (heavy)
Accumulation (severe)
Delayed peak



30s Wingate test

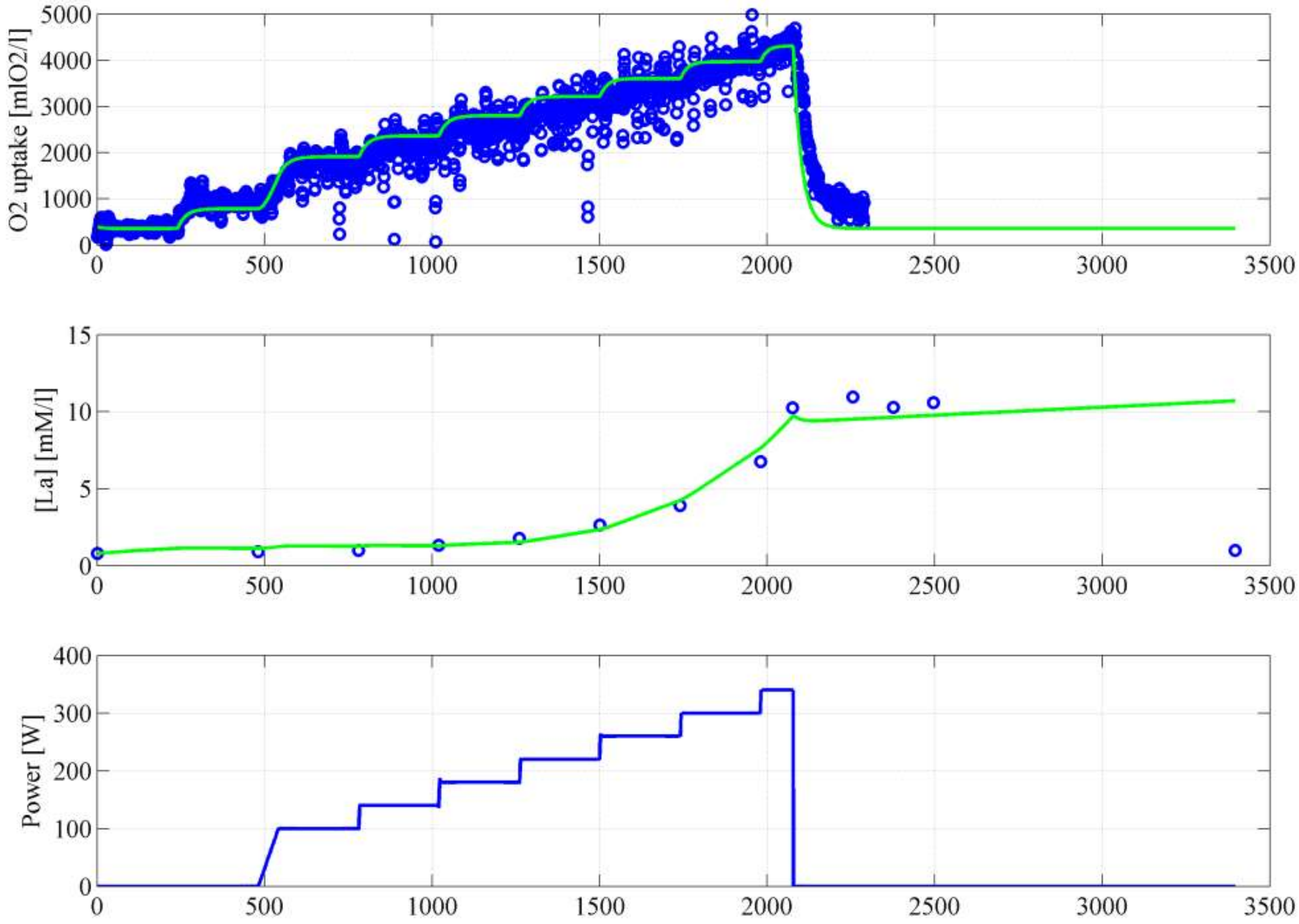
$$[La](t) = [La](0) + A_1(1 - e^{-\gamma_1 t}) + A_2(1 - e^{-\gamma_2 t})$$



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

Custom written models in incremental to exhaustion

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



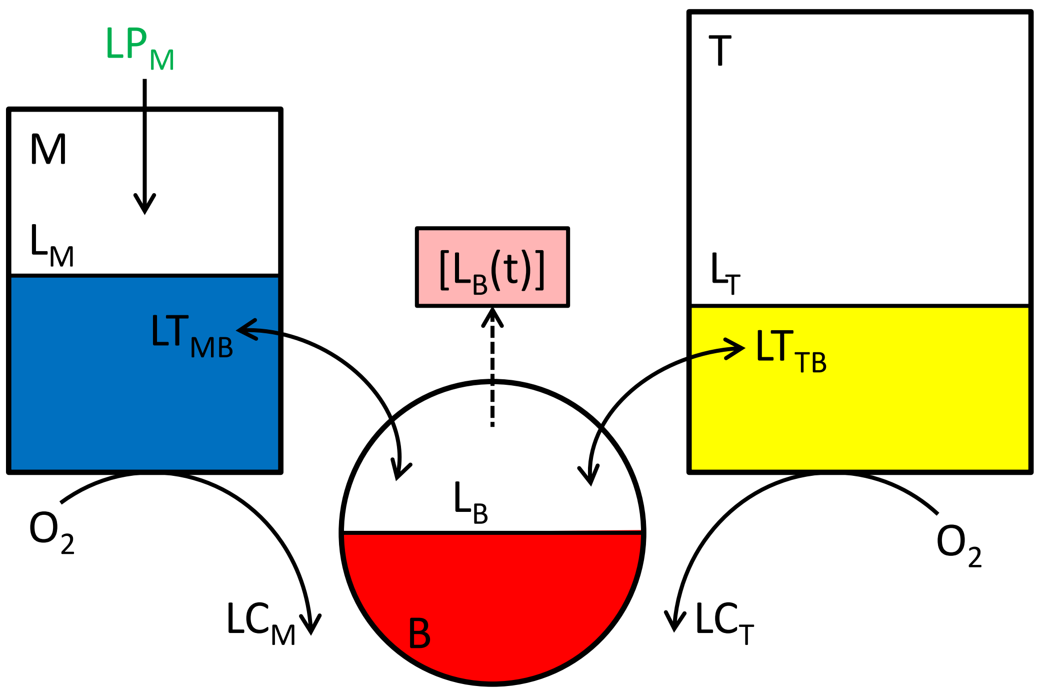
Moxnes and Sandbakk, *The kinetics of lactate production and removal during whole body exercise*, *Theor Bio Med Mod*, 2012

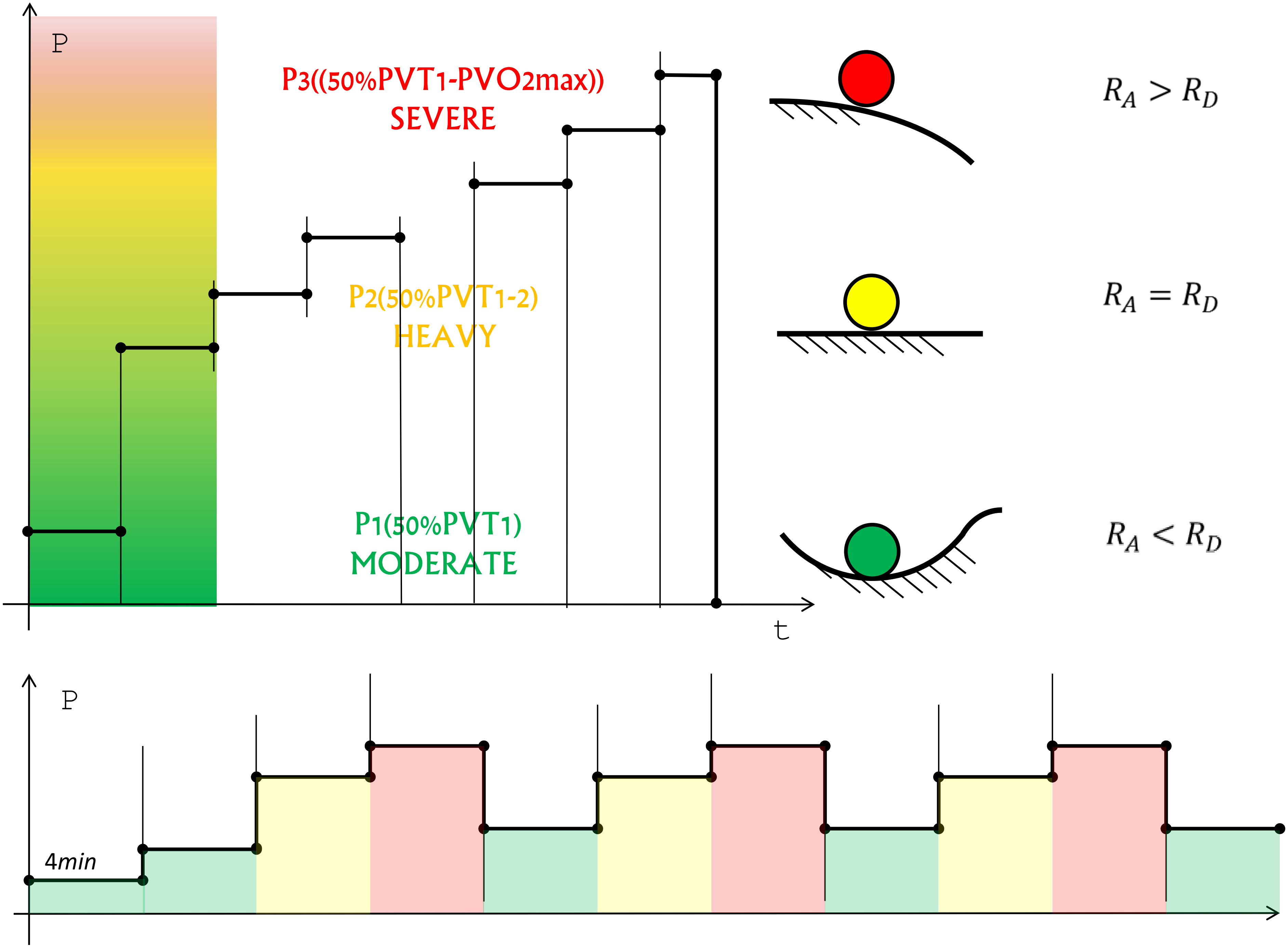
Gradient driven lactate transfer
Lactate is produced and cleared in muscles and tissues

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

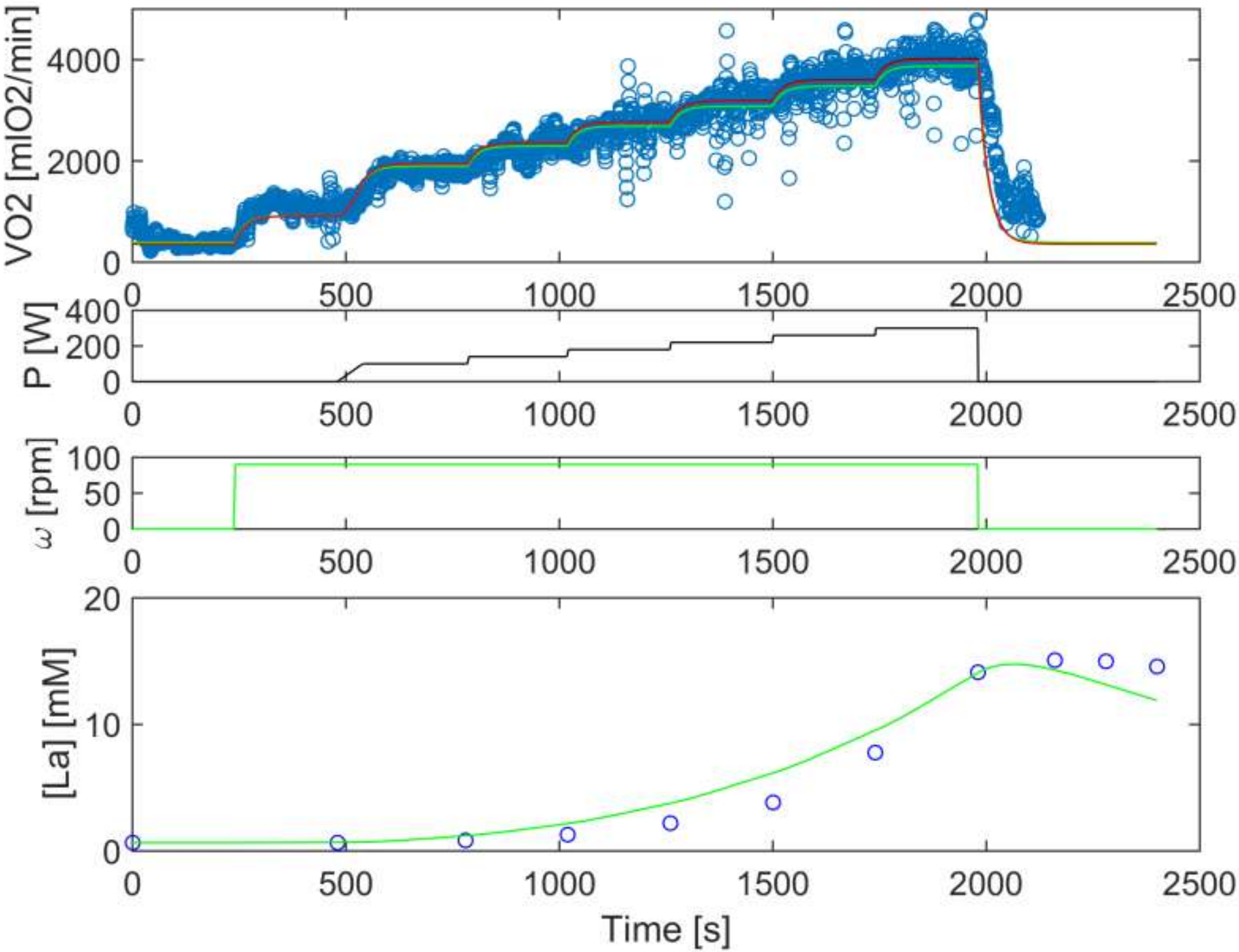
$$\Delta L_T = K_{T0}(L_T) + K_T(L_T - L_B)$$

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




P
P3((50%PVT1-PVO2max))
SEVERE
P2(50%PVT1-2)
HEAVY
P1(50%PVT1)
MODERATE
t
$R_A > R_D$
$R_A = R_D$
$R_A < R_D$
P
4min

Verification = replication



Validation = prediction

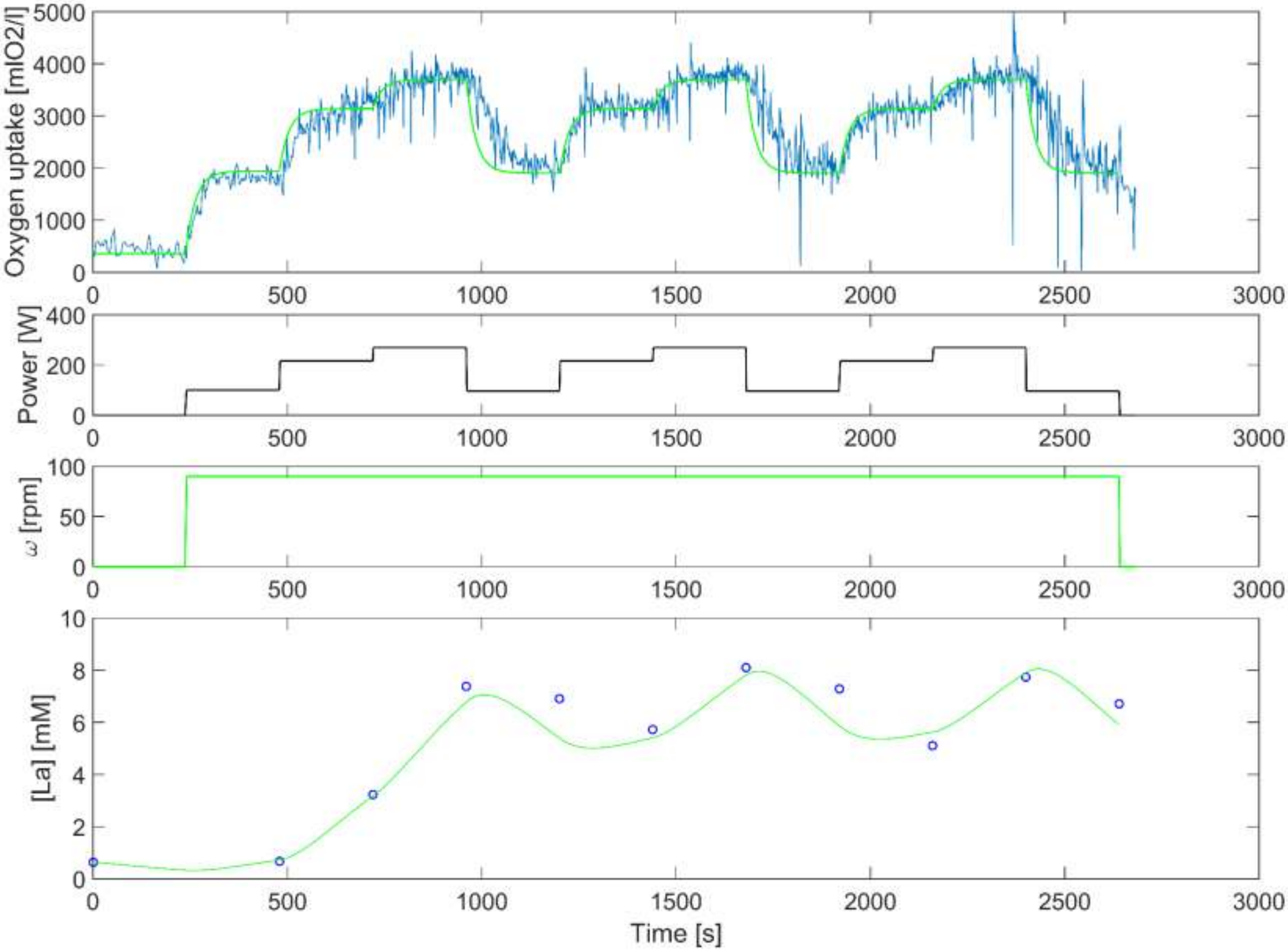


Figure 1. Three intensity zones defined by physiological determination of the first and second ventilatory turnpoints using ventilatory equivalents for O_2 (VT_1) and CO_2 (VT_2).

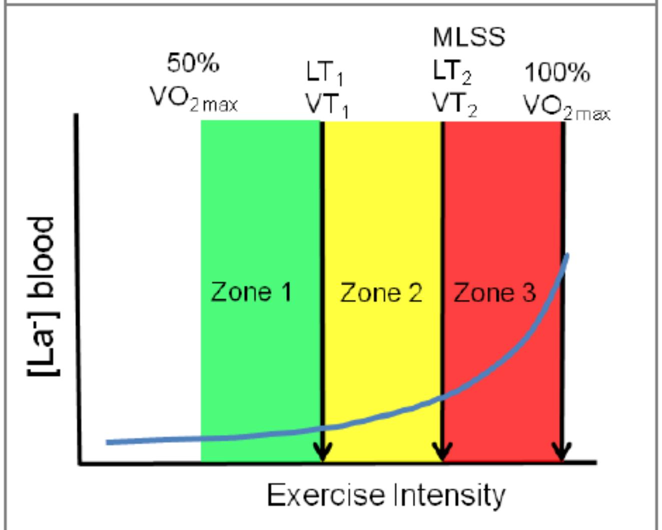


Table 1: A typical five-zone scale to prescribe and monitor training of endurance athletes.

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.

Recommendations for the design of run-based high-intensity interval training protocols with respect to blood lactate accumulation

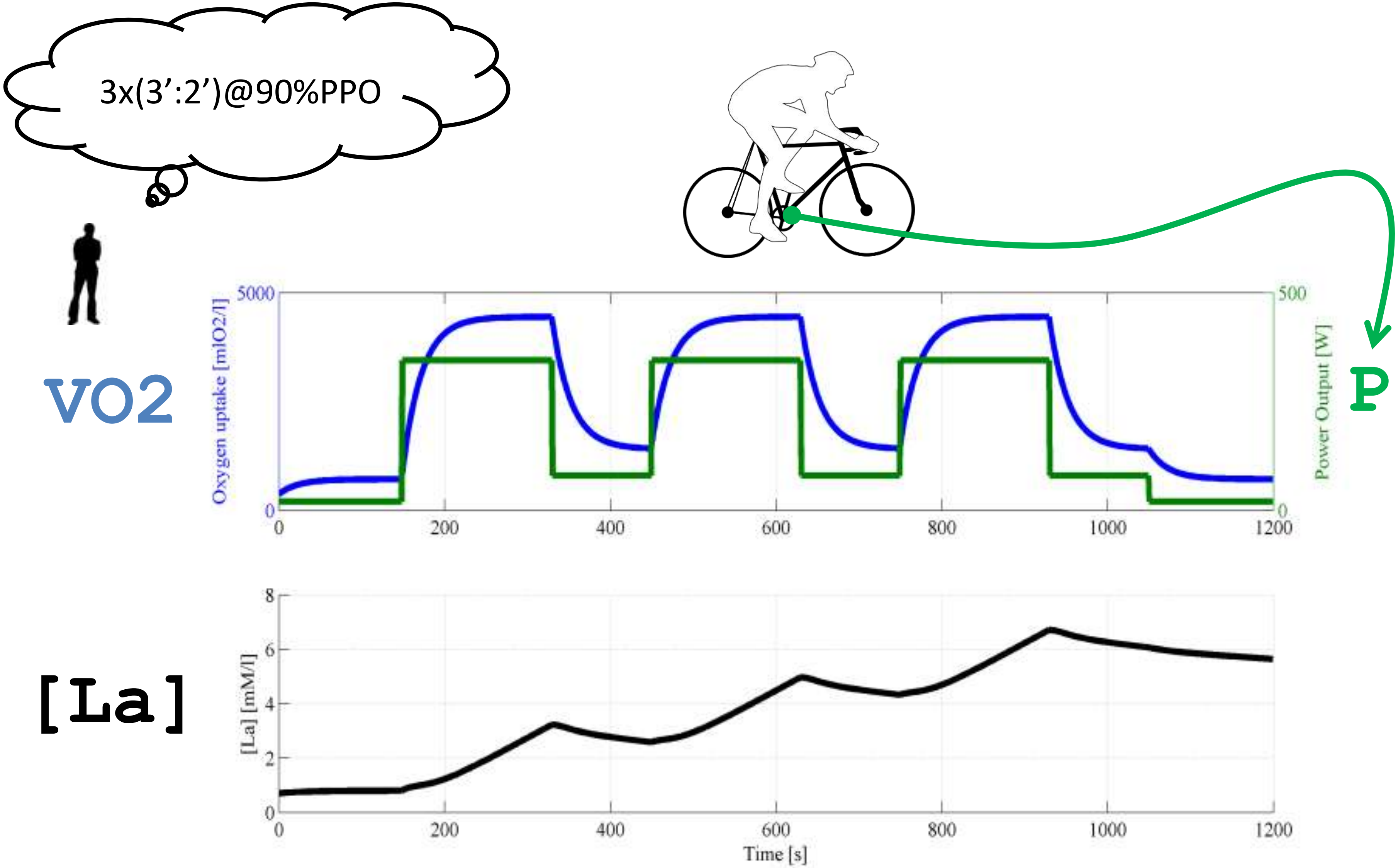
Format	Work duration	Work intensity[a]	Modality	Relief duration	Relief intensity[a]	Expected initial rate of blood lactate accumulation (mmol/L/5 min)
				≥4–5 min		
HIT with long intervals	<2 min	<100 % $v\dot{V}O_{2max}$	Straight line	2 min	Passive	≈5
HIT with short intervals	>25 s	>110 % $v\dot{V}O_{2max}$ (>90 % V_{IFT})	COD	>15 s <30 s	60–70 % $v\dot{V}O_{2max}$ (45–55 % V_{IFT})	≈6–7
HIT with long intervals	>3 min	≥95 % $v\dot{V}O_{2max}$	Straight line, sand, hills	>3 min	Passive	≈5–7
RST	<3 s	All-out	45–90° COD	>20 s	Passive	≤10
RST	>4 s	All-out	Straight line + jump	<20 s	≈55 % $v\dot{V}O_{2max}$ (40 % V_{IFT})	>10
SIT	>20 s	All-out	Straight line	>2 min	Passive	>10

[a] Intensities are provided as percentages of $v\dot{V}O_{2max}$ and V_{IFT}

COD changes of direction, *HIT* high-intensity interval training, *RPE* rating of perceived exertion, *RST* repeated-sprint training, *SIT* sprint-interval training, V_{IFT} peak speed reached in the 30–15 Intermittent Fitness Test, $v\dot{V}O_{2max}$ lower speed associated with maximal oxygen uptake

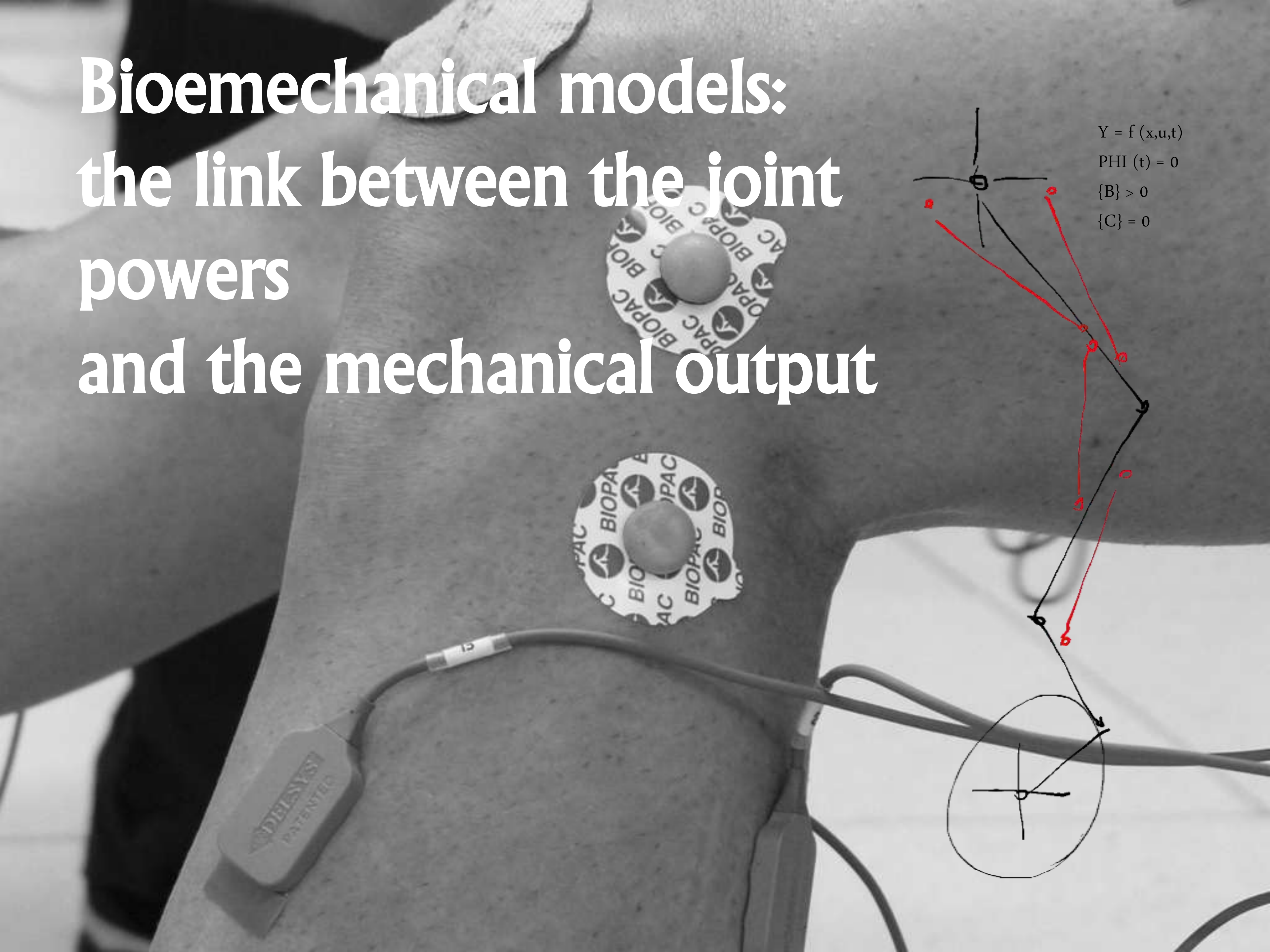
Seiler, *What is best practice for training intensity and duration distribution in endurance athletes, Int J Sports Physiol Perform* 2010

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



n	S.N.	Age [aa]	Weight [kg]	Height [cm]	PPO [watt]	PO_VT1 [watt]	PO_VT2 [watt]	Lact Bas [mmol/l]	Lact Peak [mmol/l]
1	F.A.	25.5	80	181	356	210	265	0.9	11.3

Bioemechanical models: the link between the joint powers and the mechanical output



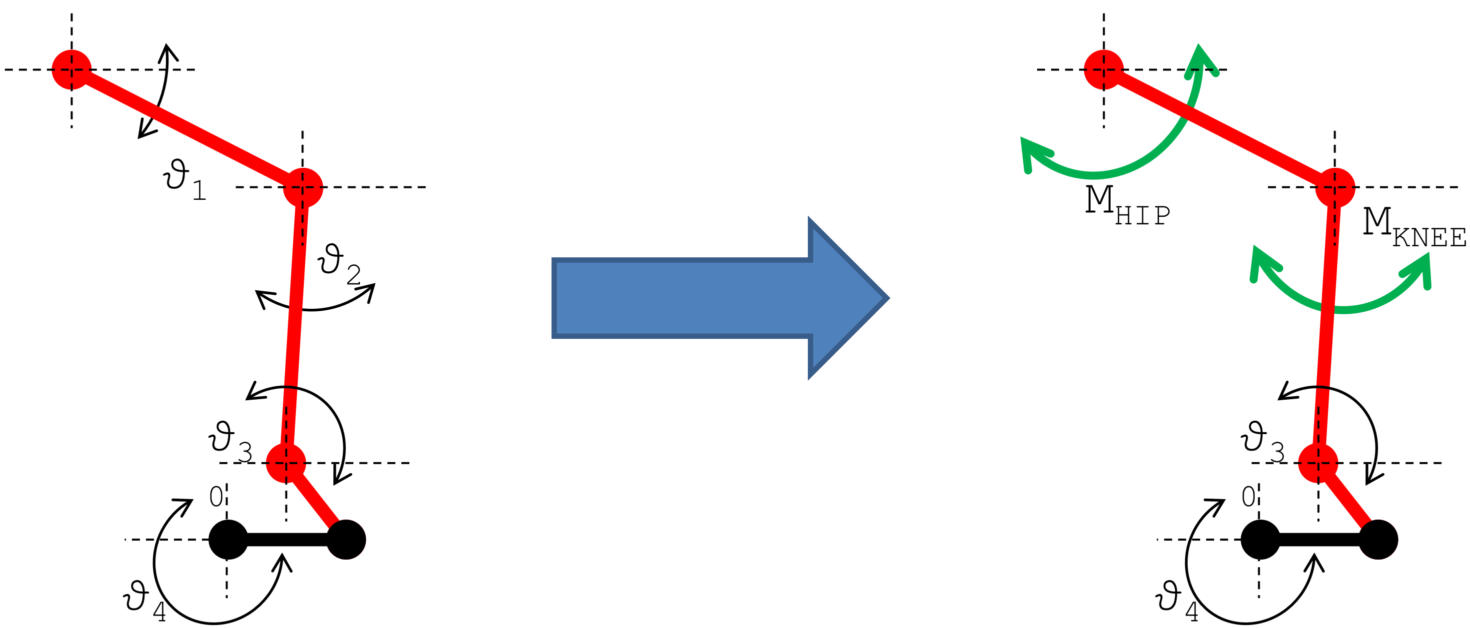
Movement synthesis:

- Kinematic (assembly, static, ROMs, etc.)
- Dynamic (inverse, direct, etc.)
- Control (strategy)

A central problem of the dynamic analysis is the inverse dynamics problem:

i.e.: find the joint torques that allow for that movement.

Kinematic measurements → Joint torques



Solving for the inverse dynamics requires the solution to the abundance (redundancy, optimality).

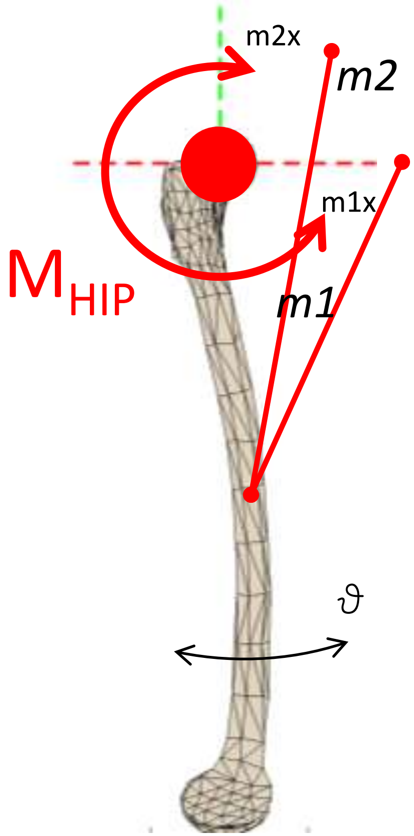
- This is because human body is built with a structure that allows with more available solution than needed for the single tasks and then the body has the ability to find the the task-specific variables to the solution.

- Anatomical level (more muscles are wrapping the same joint)
- kinematic level (different trajectories)
- Neurophysiological level (multiple motoneurons are synapsing on the same muscle)

The body solves for this problem naturally but…From the mathematical point of view we say that the system is underdetermined.

We solve for underdetermined problems with optimization

Pandy M.G. et al., *A parameter optimization approach for the optimal control of large-scale musculoskeletal systems, ASME*, 1992



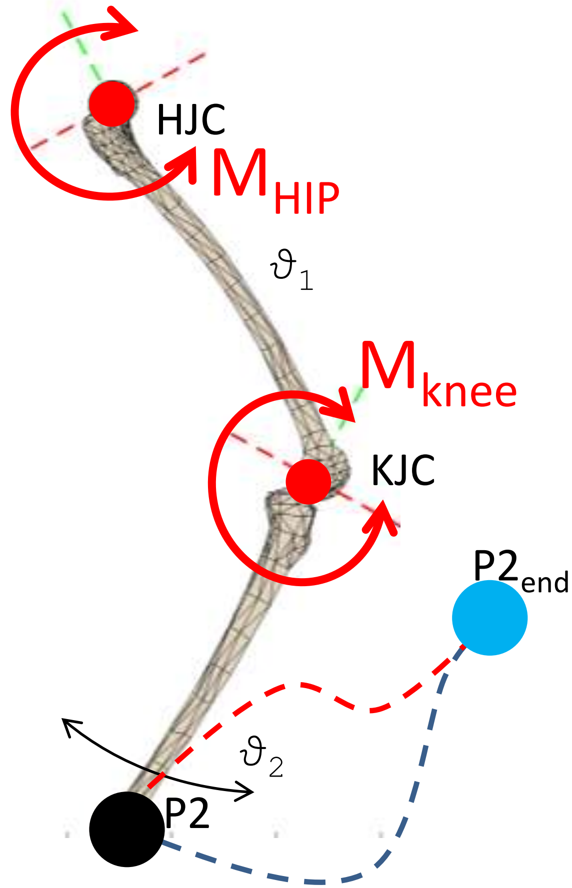
1 body

1 degree of freedom

1 input

2 inputs

We need a criteria for the muscle forces



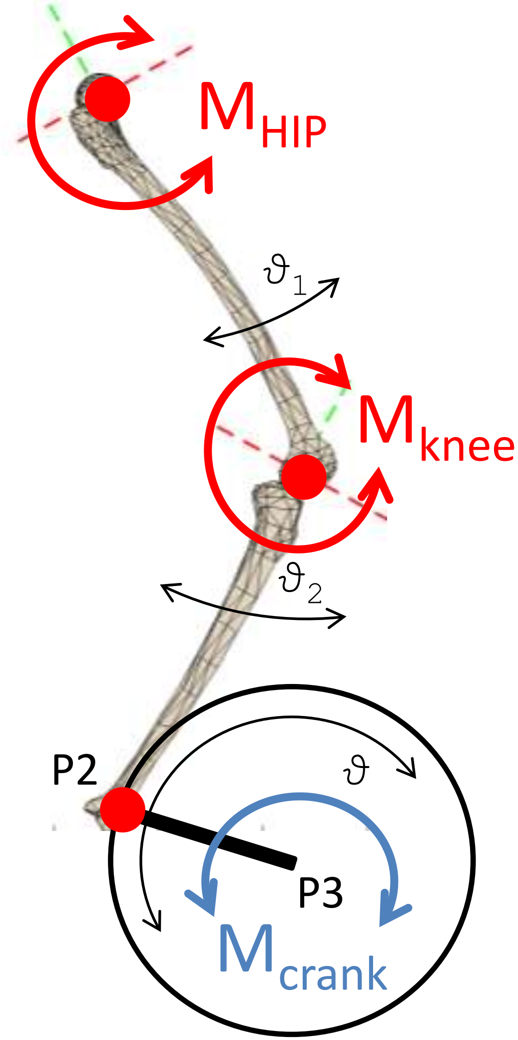
2 bodies

2 degrees of freedom

2 inputs

Infinite pathways

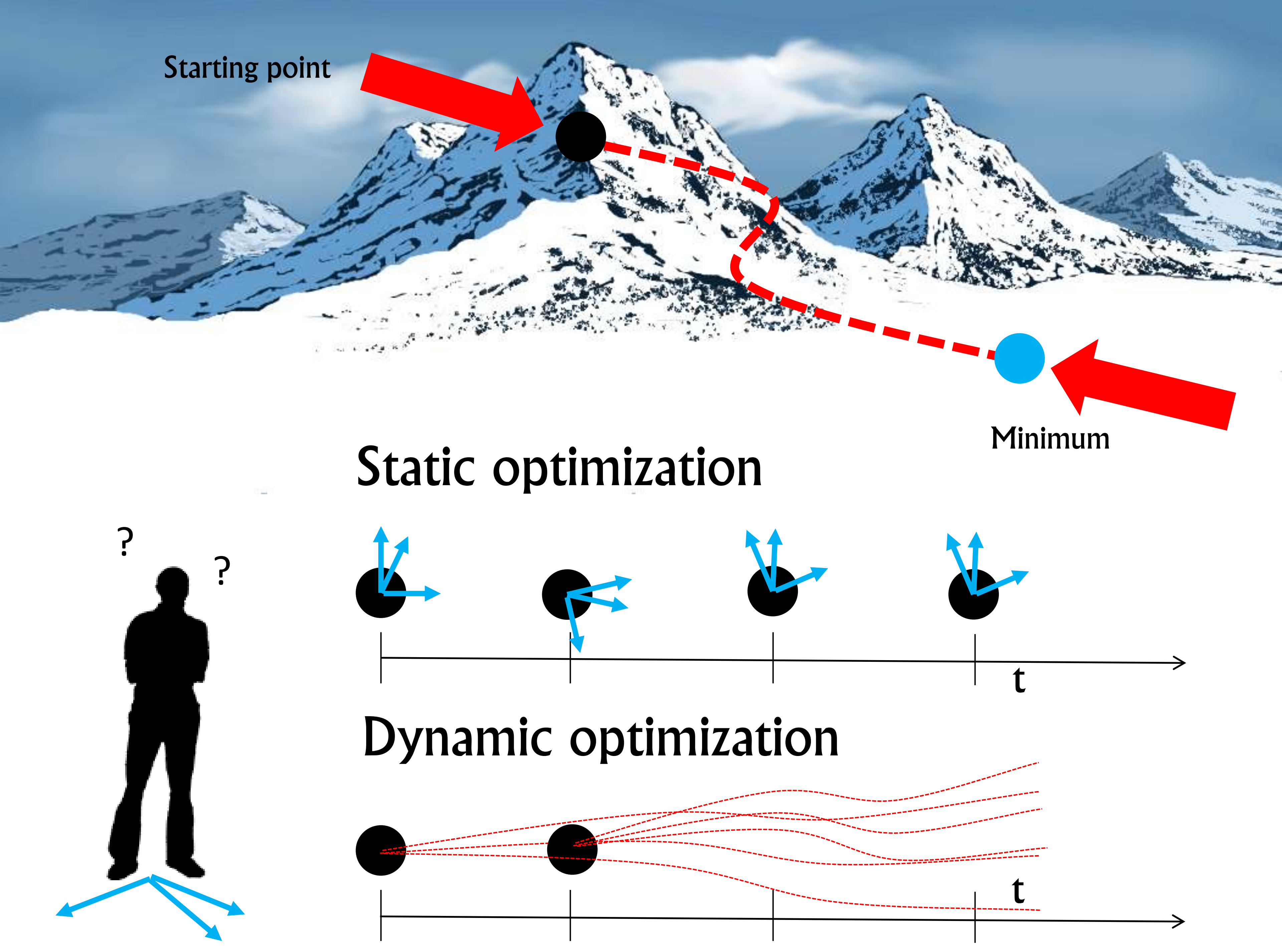
We need a criteria for the path



3 bodies

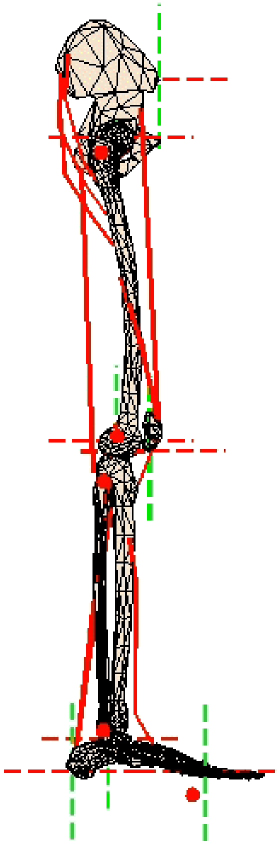
1 degrees of freedom

2 inputs

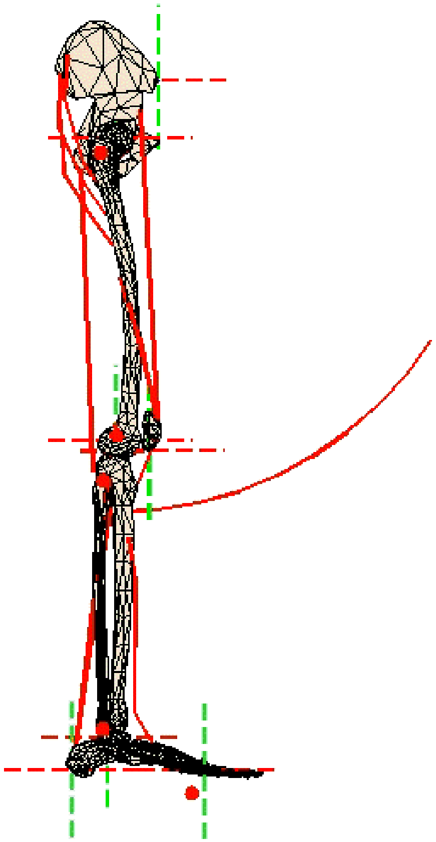


Starting point
Minimum
Static optimization
?
?
t
Dynamic optimization
t

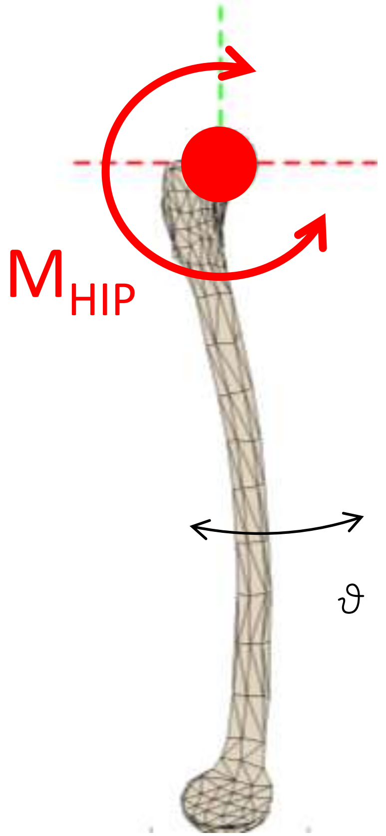
Static optimization

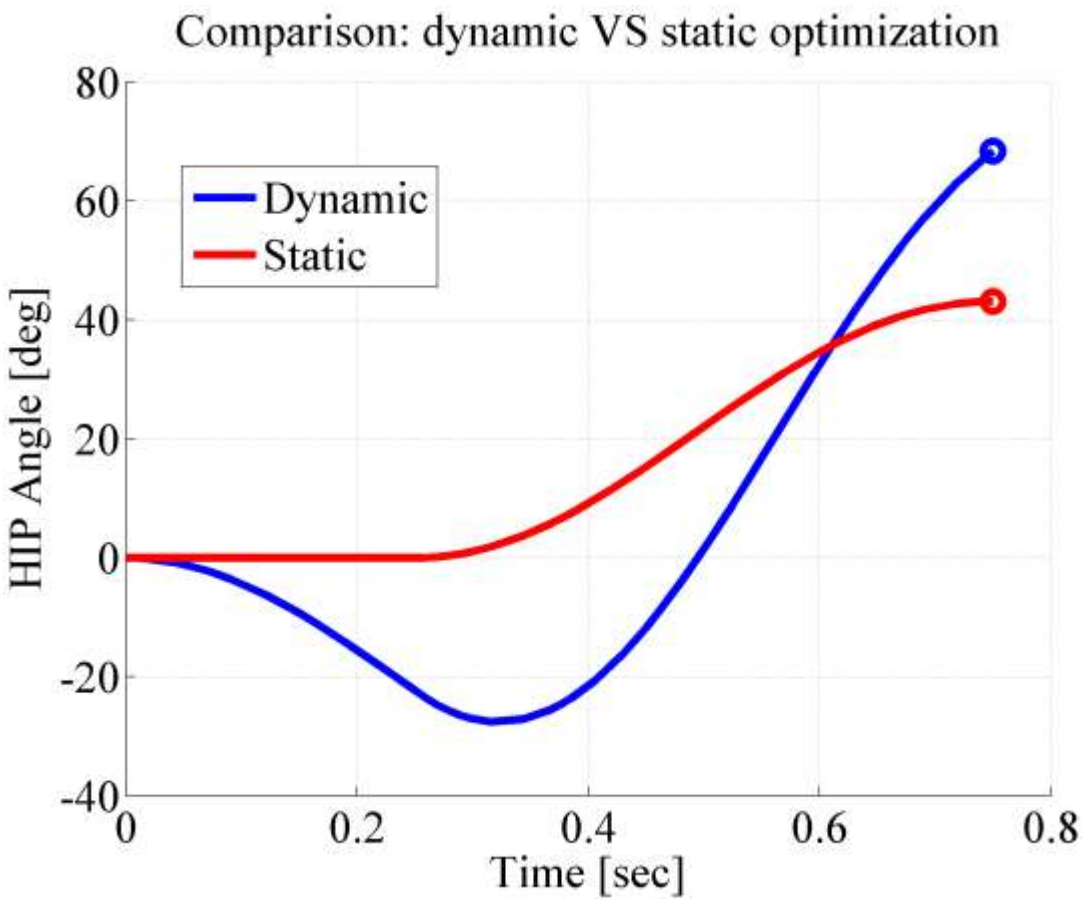


Dynamic optimization



Static and dynamic optimization





Idea credits: Todorov E., *Nature*, 2004

Elements of the optimization problem:

Task (be accurate, “go as fast as you can”)

Dynamic equations (ground reaction, gravity, etc…)

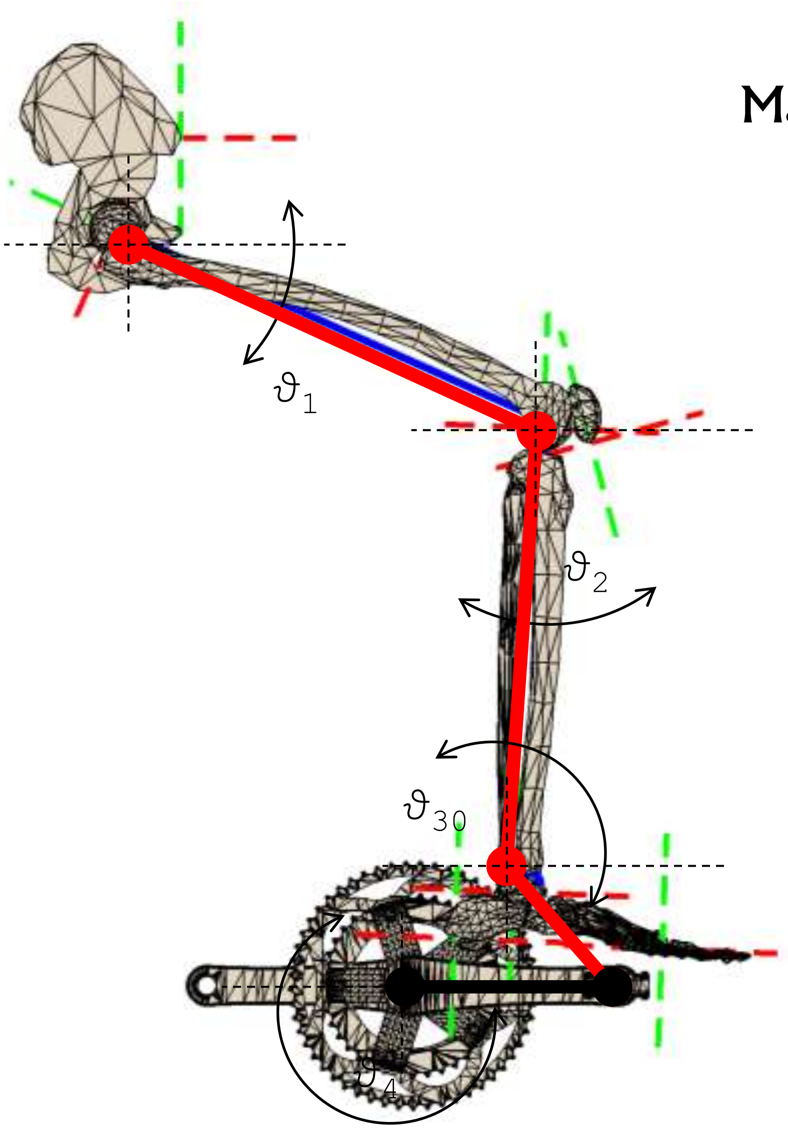
$$L = \Phi + \lambda\left([\mathbf{M}]\{\dot{\mathbf{x}}\} - \boldsymbol{f}(t, x, u, p) \right)$$

1. Minimize the difference with the experimental data
2. Minimize joint torques
3. Minimize the jerk
4. Minimize the variance between trials

Todorov E., *Nature*, 2004

Kinematic closed chain

Matrix [M] invertible → Matrix [M] singular

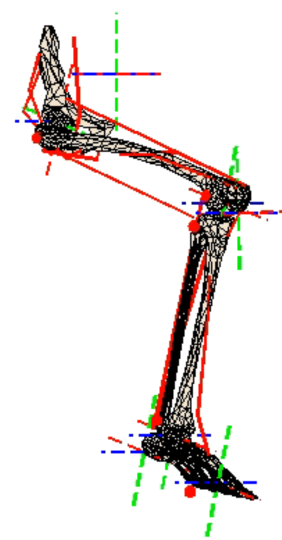


Both legs:

3 degrees of freedom

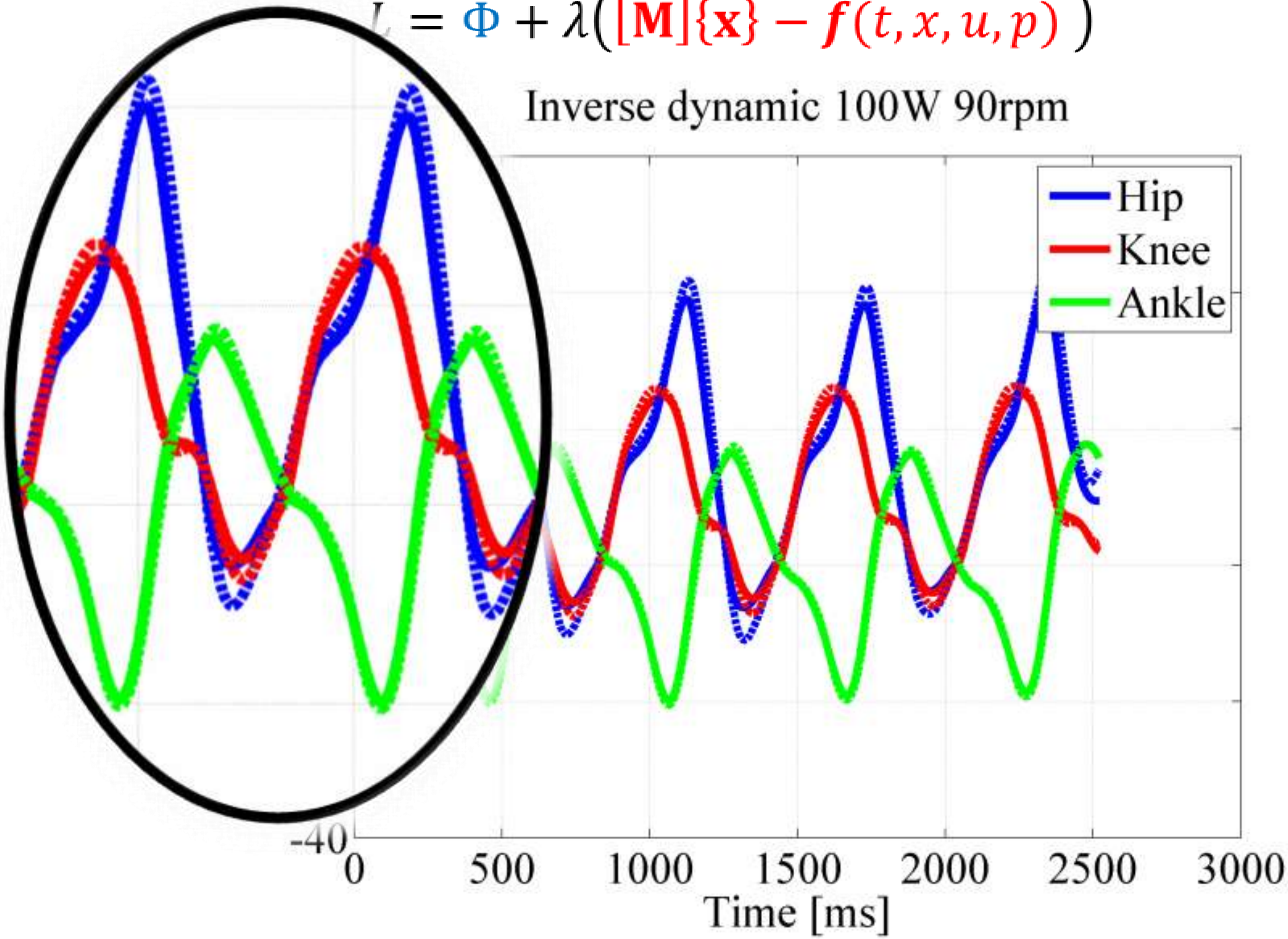
4 inputs

(hip torques, knee torques)



In the inverse dynamic problem we can have then two error sources: the system dynamics and the functional

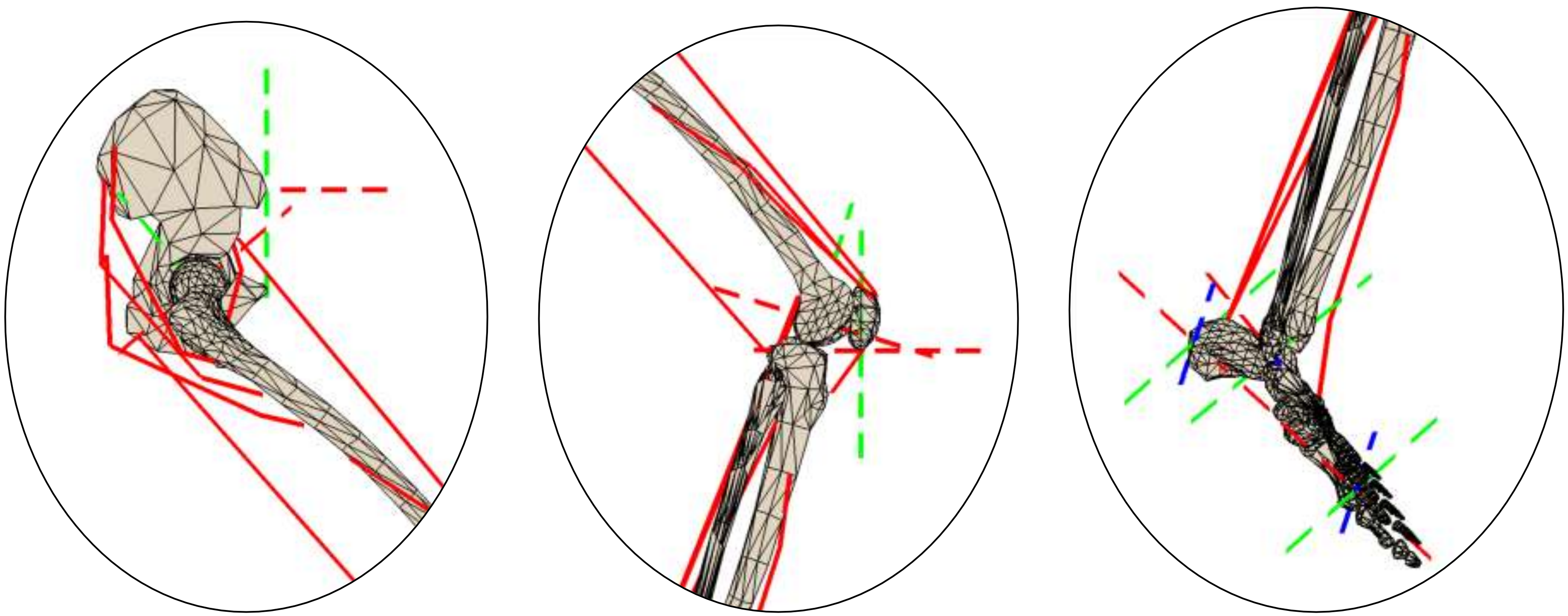
$$L = \Phi + \lambda\left([\mathbf{M}]\{\dot{\mathbf{x}}\} - \boldsymbol{f}(t,x,u,p)\right)$$



1. Dynamic optimization is advised for rapid movements
2. Two different sources of error
3. Net muscle joint torques VS muscle force coordination

Muscle:

1. PCSA
2. MA
3. Fiber %
4. FL
5. TSL



Fregly B.J. and Zajac F.E., *A state space analysis of mechanical energy generation, absorption, and transfer during pedaling, J. Biomechanics*, 1995

Best position on the bike with only kinematic measurements?

We know that the same kinematic solution can be obtained with different torques.

We can study the torques with the inverse dynamics.

We need:

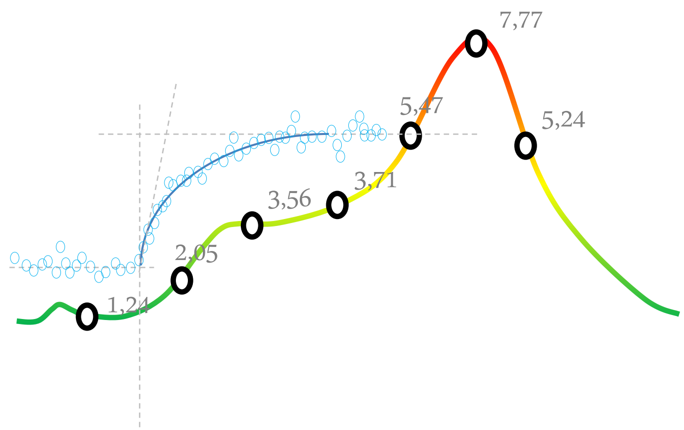
1. a very detailed geometry to solve the problem in the muscle forces
2. a very fast solver for the inverse dynamic solution

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

Acknowledgments

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Azim Jinha (University of Calgary, Calgary)

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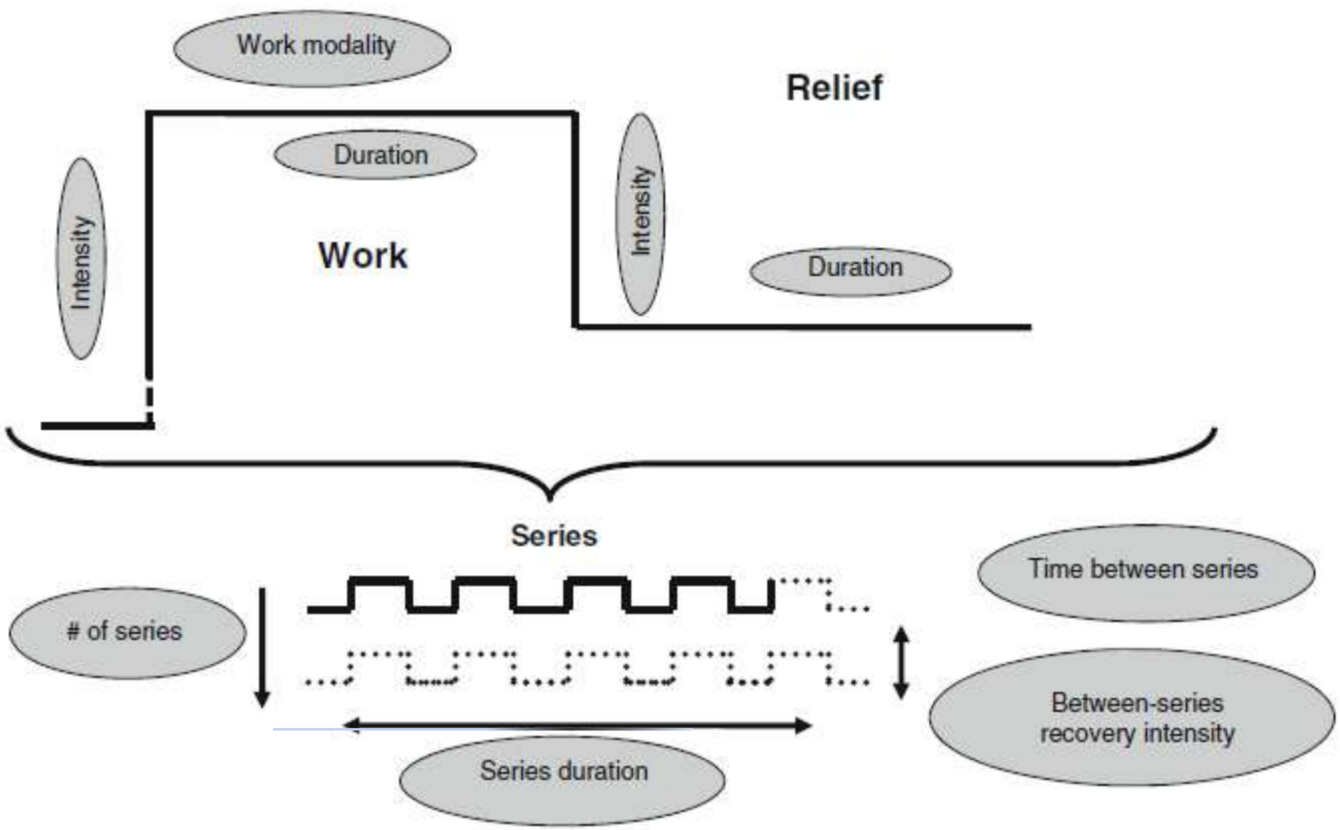
Fact: There has been a growing interest by the sport science community for characterizing training protocols that allow athletes to maintain the longest time >90% $\dot{V}O_{2MAX}$.

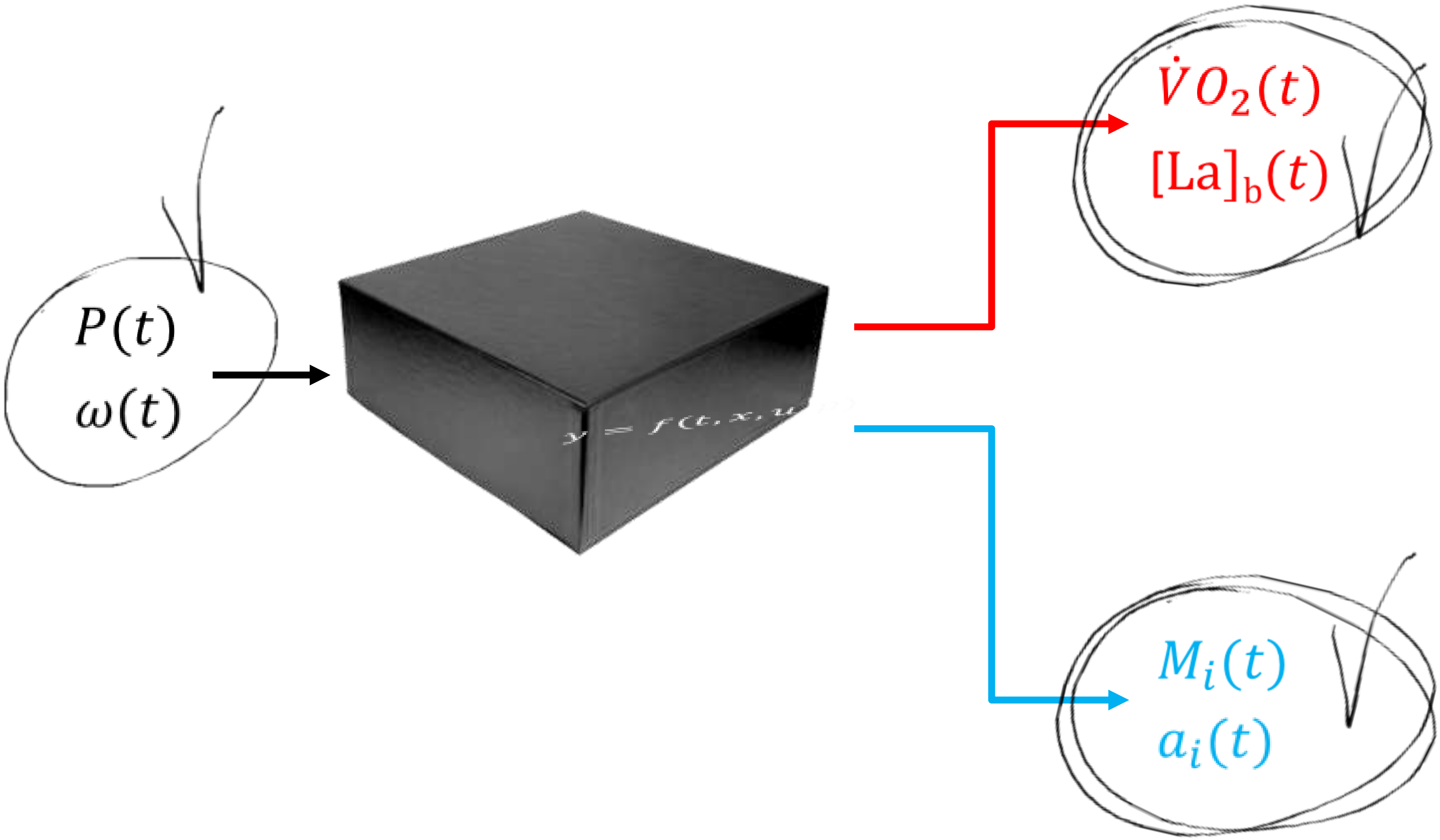
Question: Can we find the best combination of parameters which allows the athlete maintaining the maximal value of T@$\dot{V}O_{2MAX}$?



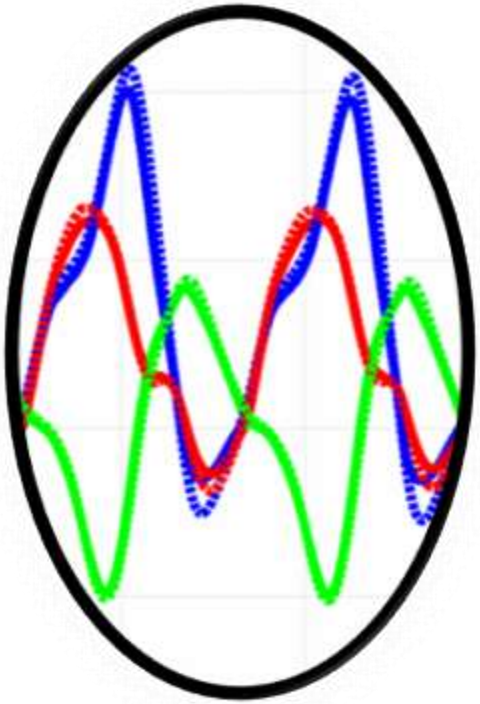
Fact: On July 17th 2013 Chris Froome bested Alberto Contador of 9 seconds in TT Embrun. He switched during the course from a Pinarello Dogma 65.1 to Bolide TT bike. He was 11 seconds down and he spent 15 seconds in the bike switch. He finished 10 seconds faster.

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

Fact: On June 7th 2015 Bradley Wiggins cycled 54.526 kilometers in a hour.
Question: can we predict the average power provided?



$P(t)$
$\omega(t)$
$\dot{V}O_2(t)$
$[\mathrm{La}]_{\mathrm{b}}(t)$
$M_i(t)$
$a_i(t)$

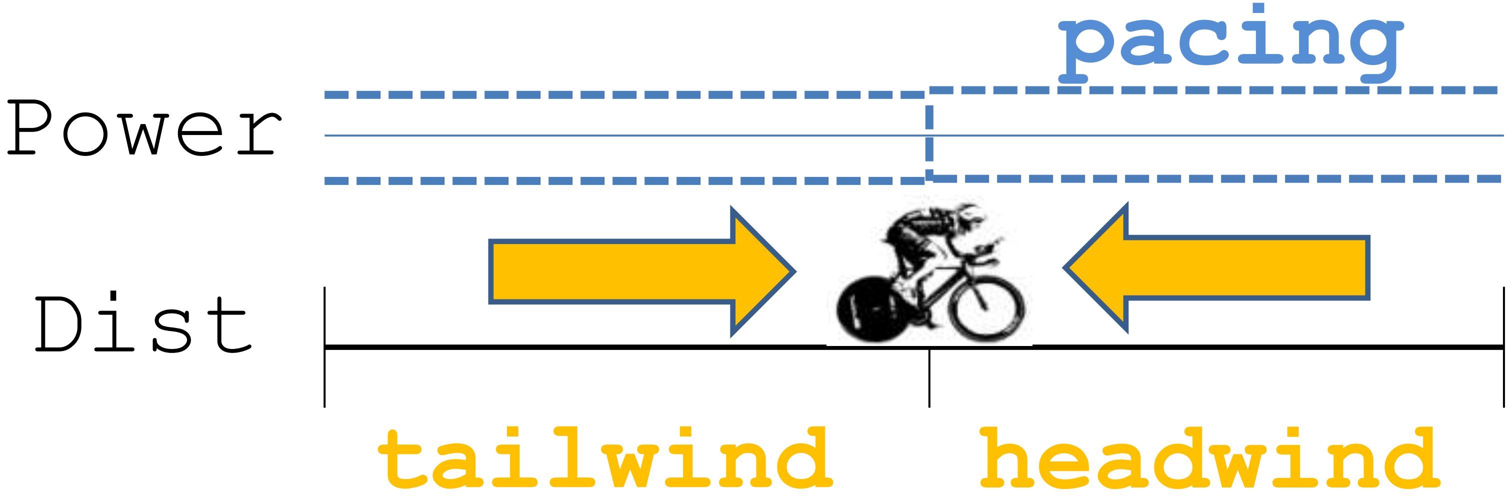


We can obtain different solution for the same kinematics. It depends on the cost function and on the model dynamics.

$$L = \Phi + \lambda\left([\mathbf{M}]\{\dot{\mathbf{x}}\} - \boldsymbol{f}(t, x, u, p)\right)$$

Unfortunately rule out the biarticular muscles.

Anderson F.C. and Pandy M.G., Static and dynamic optimization solutions for gait are practically equivalent, *Journal of Biomechanics*, 1999



Suggestion based on the equation of motion (e.g. Old, Di Prampero, Martin):

First half -5%

Second Half +5%

- **Suggestion based on the multilevel modelling**

Dependencies: goals, race duration

If the effort is hard to face a different pace is suggested, if a limited work is imposed. Save energies in the headwind half, and push more in the tailwind half.

Atkinson and Brunskill, *Pacing strategies during a cycling time trial with simulated headwinds and tailwids*, *Erg* 2000