IRONMAN WORLD CHAMPIONSHIP MEDICAL SYMPOSIUM

Physiological Basis of Endurance Performance: A Primer

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Disclosures

None

Learning Objectives

1) To explain the physiological basis of endurance performance.

2) To interpret how training and other manipulations alter the main determinants of endurance performance.

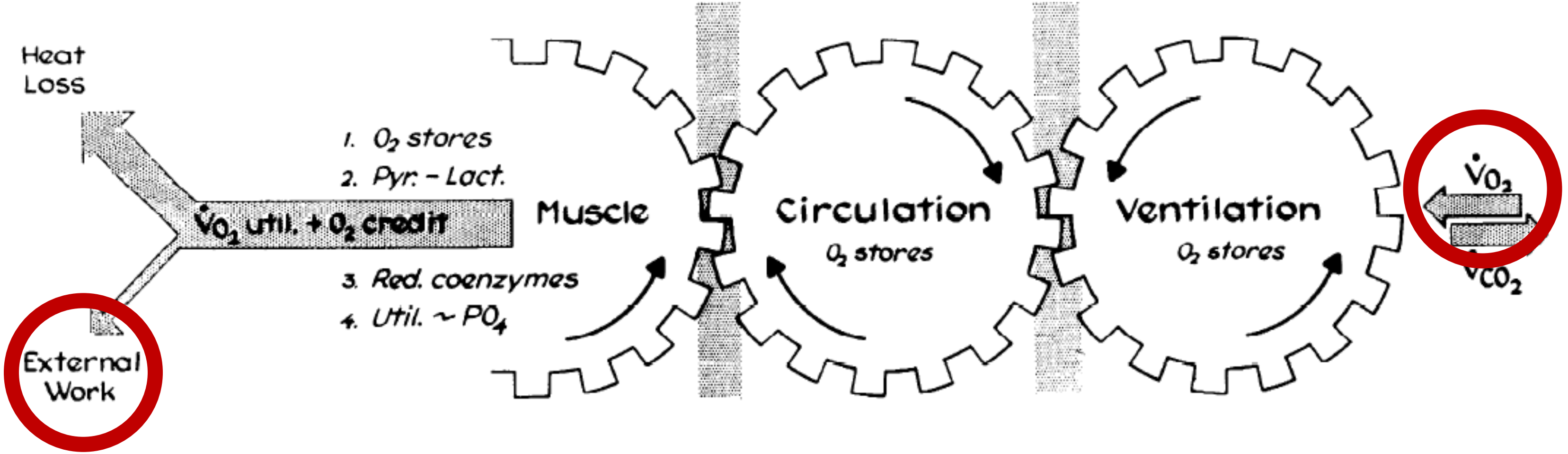
“The best predictor of performance is performance”

– Andrew Coggan, PhD; *Inside Exercise* podcast

https://www.youtube.com/watch?v=-6DhfMJH84E&t=3s
https://open.spotify.com/episode/0O35XI29hAikK9LQxX1Z9f

Physiological Determinants of Endurance Performance

Wasserman's classic "gears" analogy



Wasserman et al. J Appl Physiol 1967. doi: 10.1152/jappl.1967.22.1.71.

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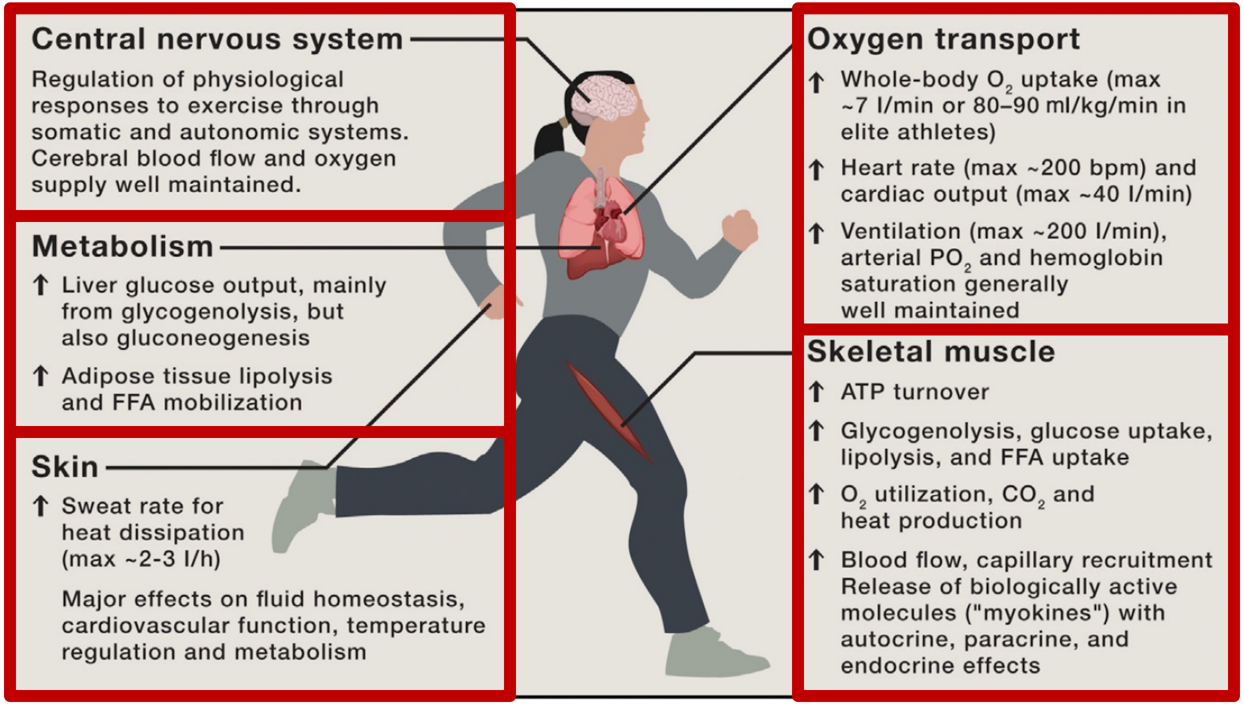
Physiological Determinants of Endurance Performance



Hawley et al. Cell Metab 2014. doi: 10.1016/j.cell.2014.10.029.

Physiological Determinants of Endurance Performance

The ‘ceiling’ for aerobic metabolism

→ Maximal oxygen uptake (VO_{2max})

i.e. Cardiorespiratory fitness

How close to the ceiling you can work

→ Fractional utilization of VO_{2max} (%)

i.e. ‘Metabolic fitness’

Oxygen transport

- ↑ Whole-body O_2 uptake (max ~7 l/min or 80–90 ml/kg/min in elite athletes)
- ↑ Heart rate (max ~200 bpm) and cardiac output (max ~40 l/min)
- ↑ Ventilation (max ~200 l/min), arterial PO_2 and hemoglobin saturation generally well maintained

Skeletal muscle

- ↑ ATP turnover
- ↑ Glycogenolysis, glucose uptake, lipolysis, and FFA uptake
- ↑ O_2 utilization, CO_2 and heat production
- ↑ Blood flow, capillary recruitment Release of biologically active molecules ("myokines") with autocrine, paracrine, and endocrine effects

Hawley et al. Cell Metab 2014. doi: 10.1016/j.cell.2014.10.029.

Physiological Determinants of Endurance Performance

The 'ceiling' for aerobic metabolism

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i.e. 'Metabolic fitness'

'Performance VO_2'

Highest rate of 'sustainable' aerobic energy metabolism

Hawley et al. Cell Metab 2014. doi: 10.1016/j.cell.2014.10.029.

Performance speed or power

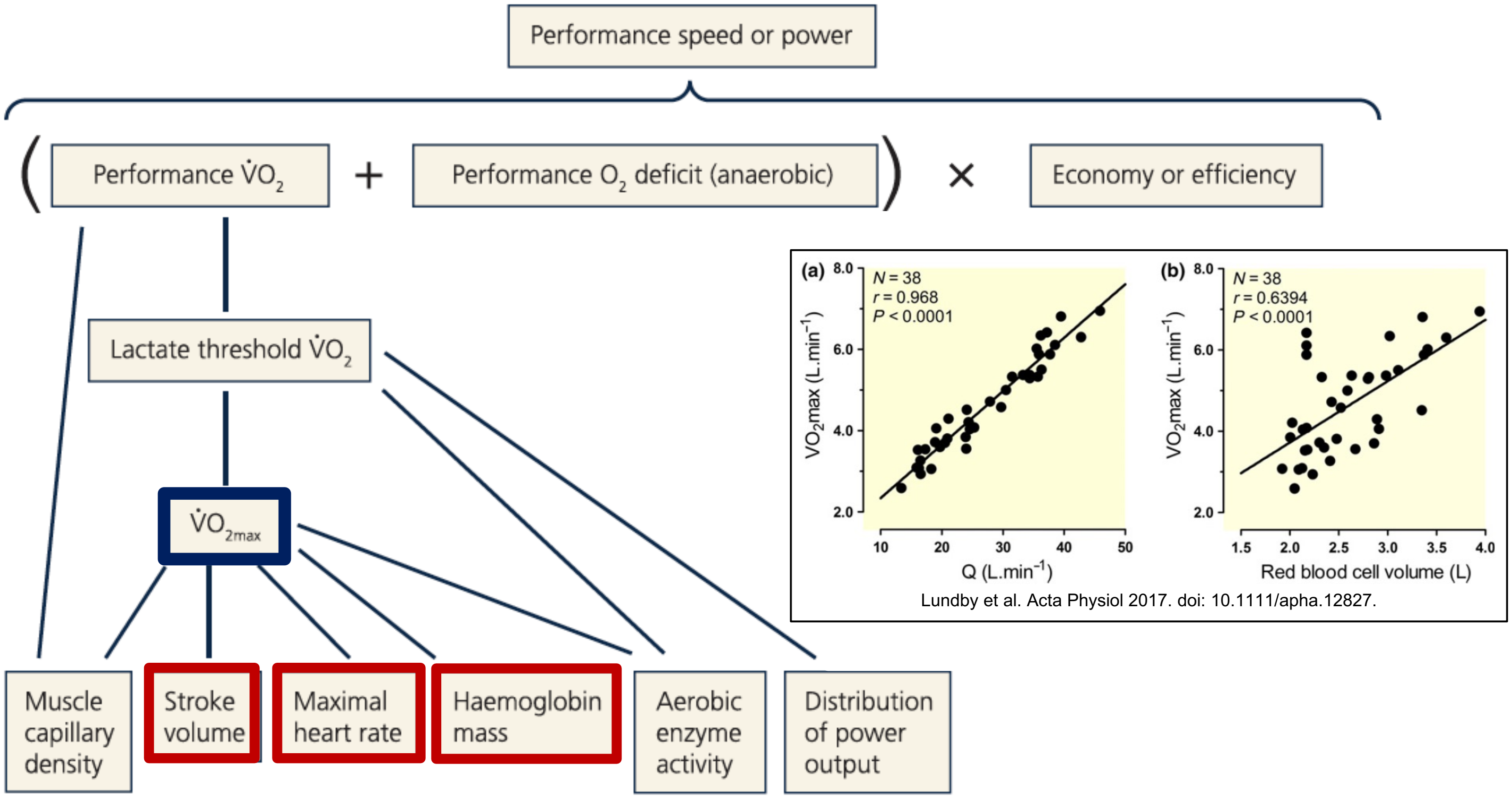
(Performance $\dot{V}O_2$

Highest rate of 'sustainable' aerobic energy metabolism

Rate of non-oxidative (anaerobic) energy metabolism

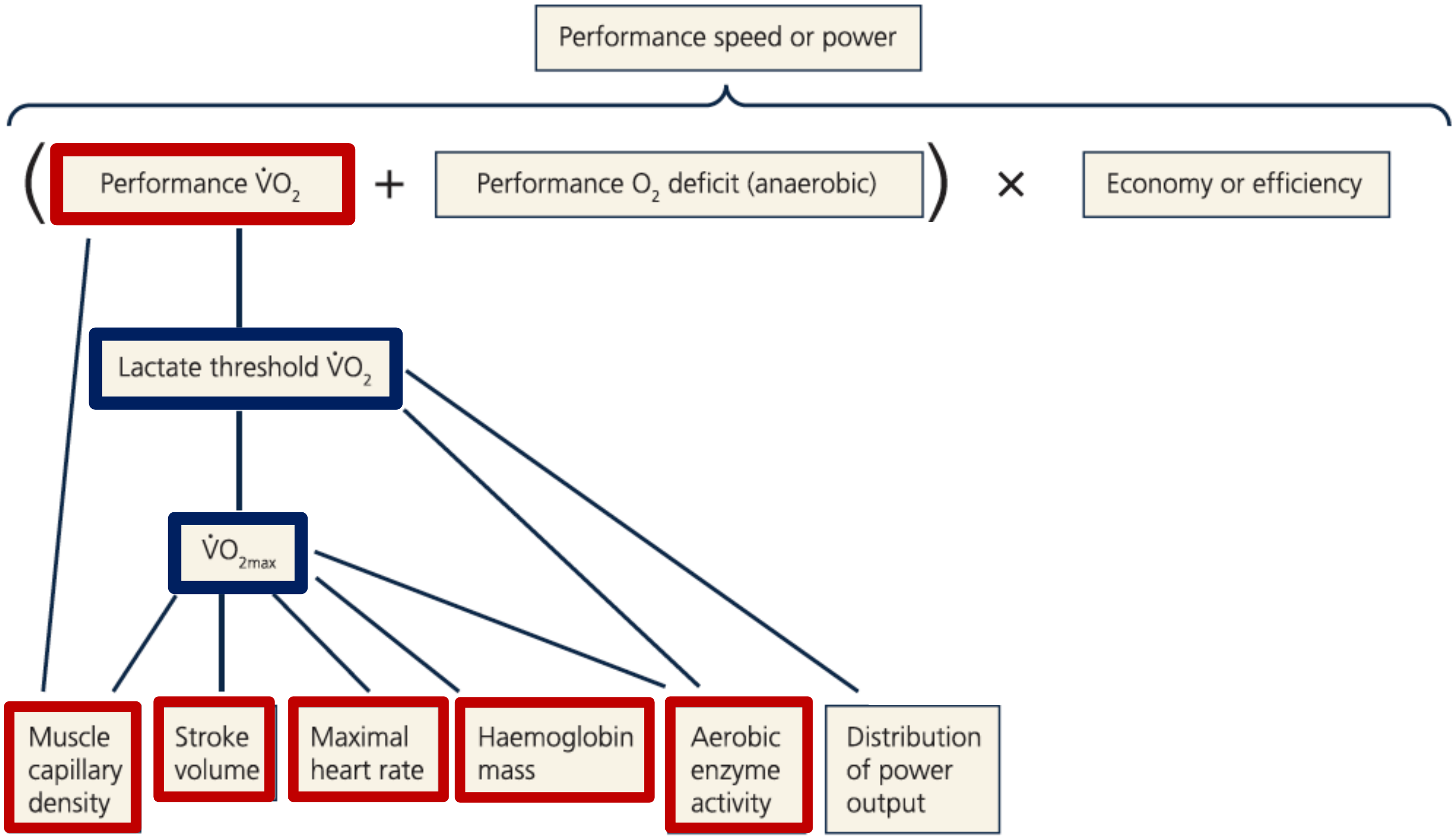
Rate of converting energy into task-specific work

Jones et al. J Physiol 2023. doi: 10.1016/j.cell.2014.10.029.
(Redrawn from Joyner & Coyle J Physiol 2008. doi: 10.1113/jphysiol.2007.143834)



Lundby et al. Acta Physiol 2017. doi: 10.1111/apha.12827.

Jones et al. J Physiol 2023. doi: 10.1016/j.cell.2014.10.029.
(Redrawn from Joyner & Coyle J Physiol 2008. doi: 10.1113/jphysiol.2007.143834)



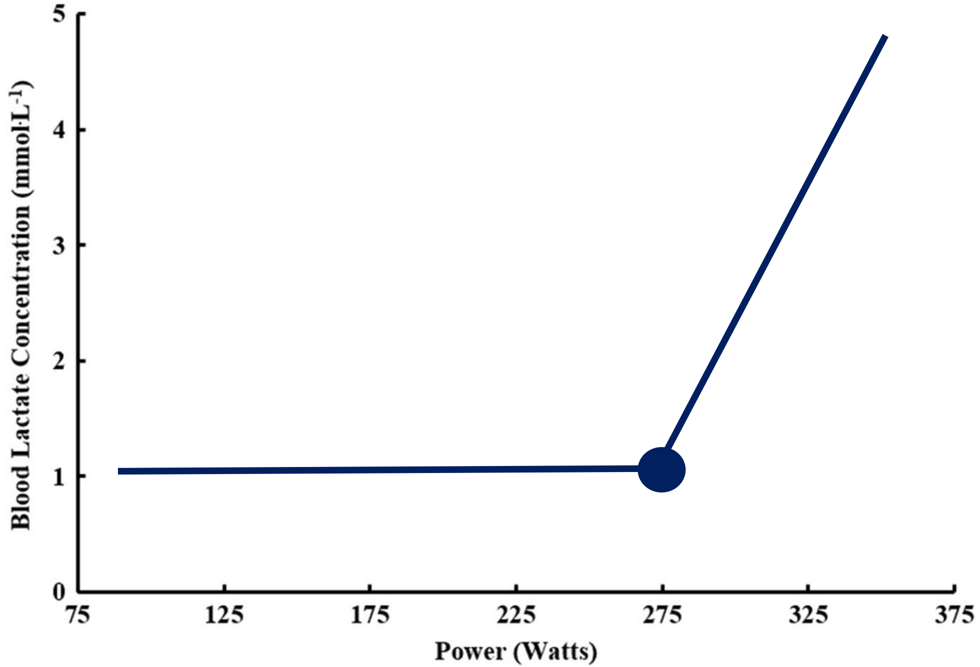
Jones et al. J Physiol 2023. doi: 10.1016/j.cell.2014.10.029.
(Redrawn from Joyner & Coyle J Physiol 2008. doi: 10.1113/jphysiol.2007.143834)

Maximal Oxygen Uptake (VO_{2max})

Martin Gibala, PhD

Martin-Rincon & Calbet Front Physiol 2020. doi: 10.3389/fphys.2020.01070 (left);
Poole & Jones. J Appl Physiol 2017. doi:10.1152/japplphysiol.01063.2016 (right).

The 'Lactate Threshold'?



Jamnick et al. Sports Med 2020. doi: 10.1007/s40279-020-01322-8.

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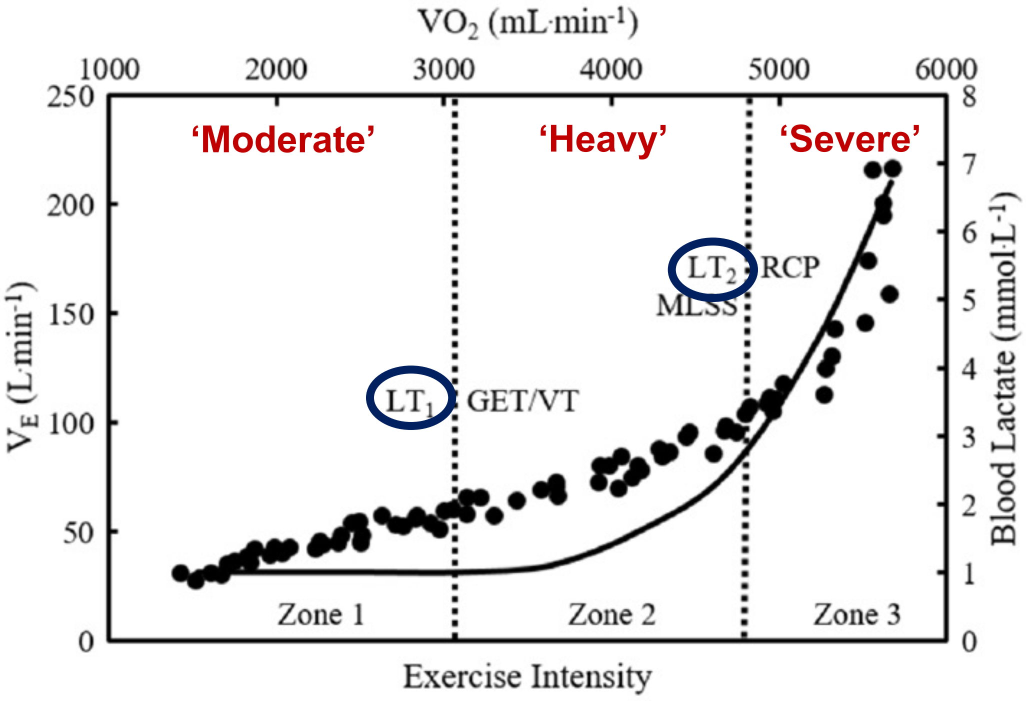
The ‘Lactate Threshold’?



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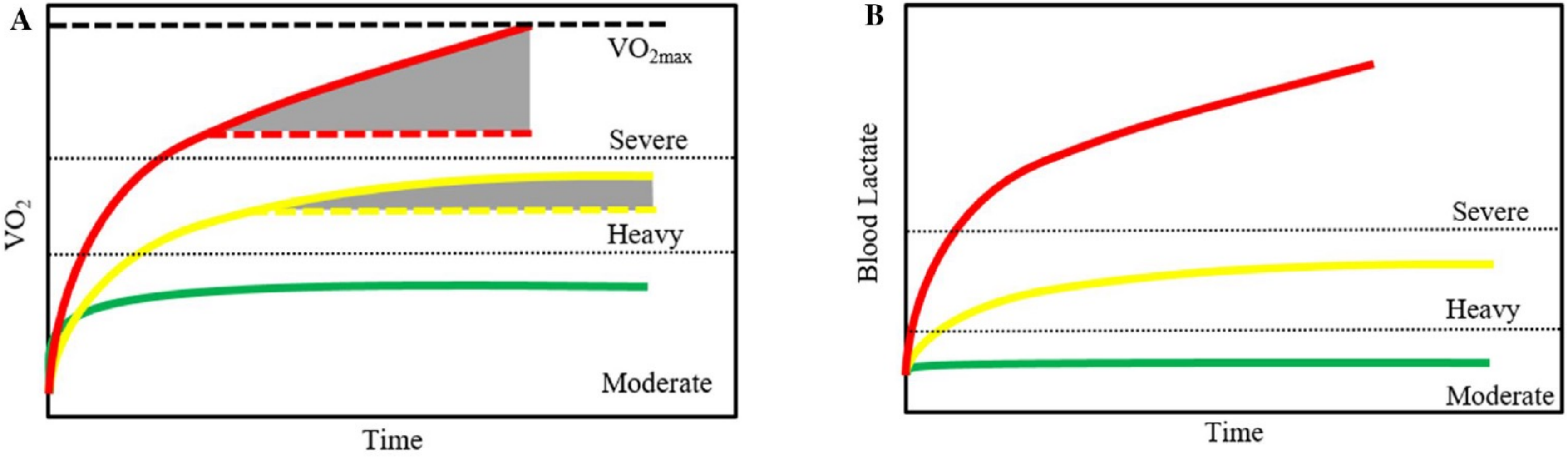
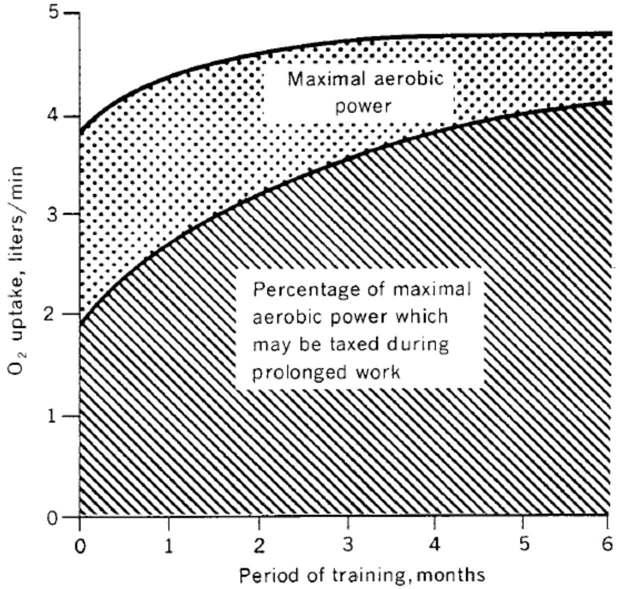
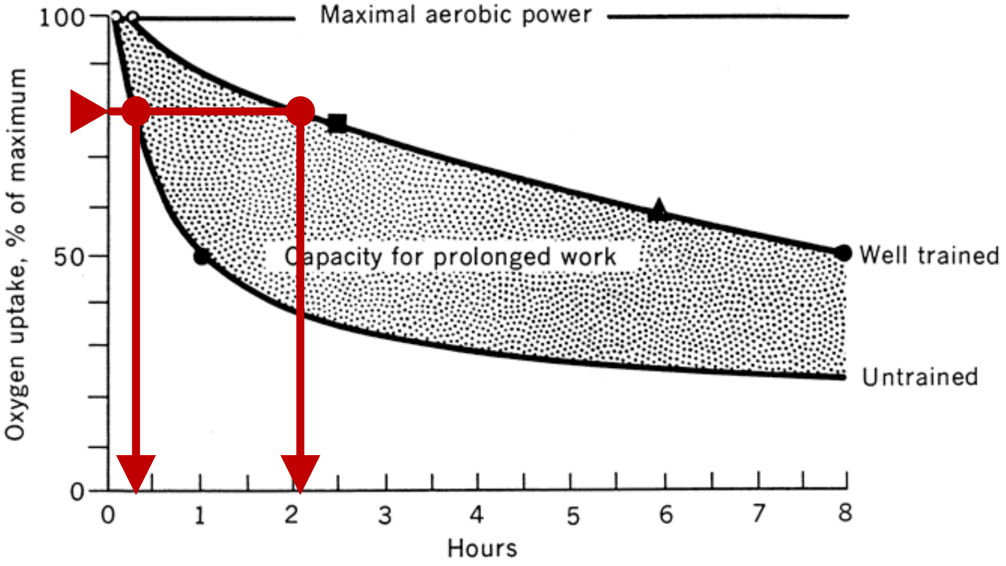


Jamnick et al. Sports Med 2020. doi: 10.1007/s40279-020-01322-8.

Effect of Endurance Training on Performance VO_2





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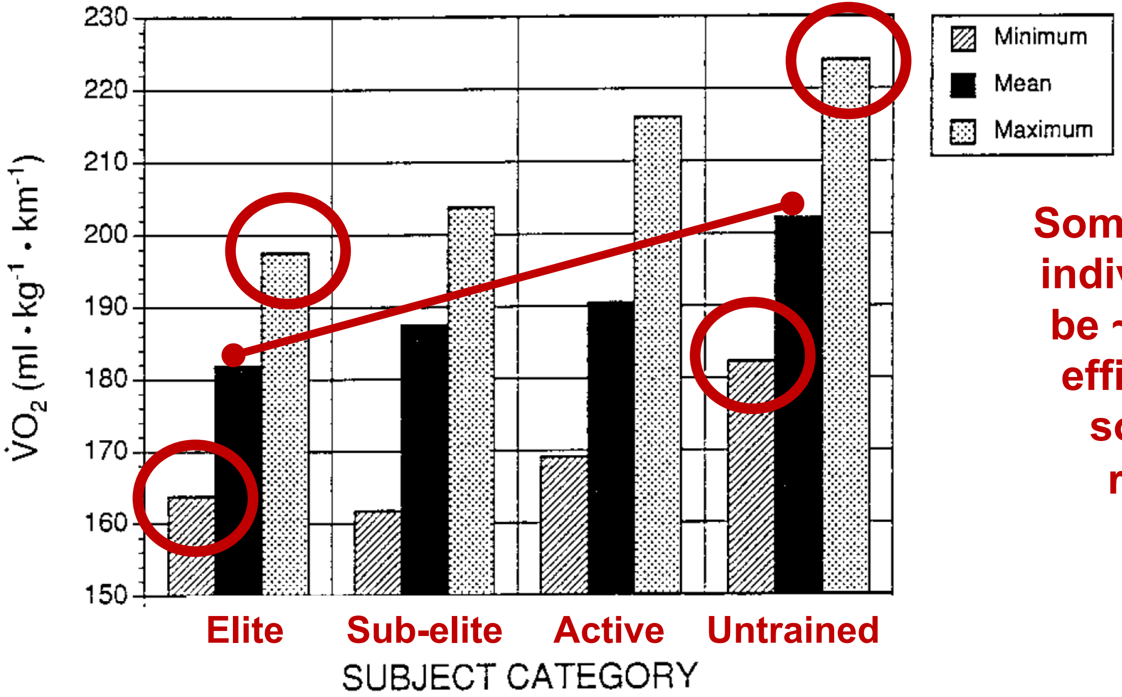
Bassett & Howley Med Sci Sports Exerc 2000. doi: 10.1097/00005768-200001000-00012.
(Based on: Astrand & Rodahl, Textbook of Work Physiology. New York: McGraw-Hill, 1970).

Mechanical Efficiency: Surprising Individual Variability

Running economy in 4 groups based on ability/training

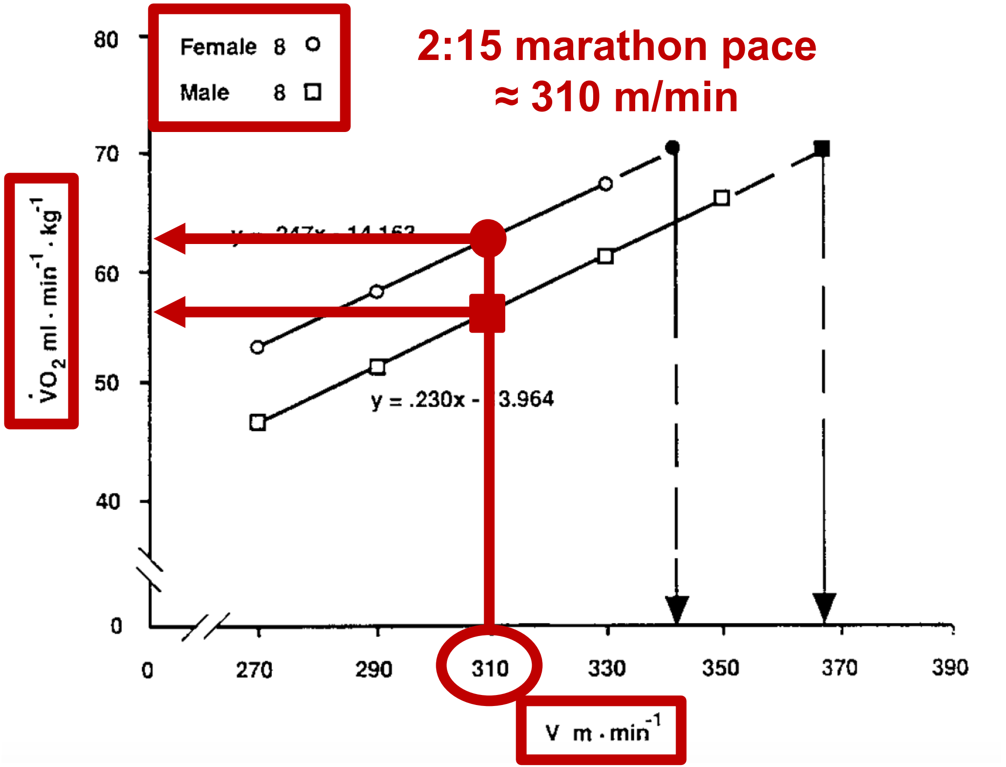
Some elite runners can be ~40% more efficient than some untrained individuals



Some untrained individuals can be ~10% more efficient than some elite runners!

Bassett & Howley, Med Sci Sports Exerc 2000. doi: 10.1097/00005768-200001000-00012.
(Based on: Morgan et al. Med Sci Sports Exerc 27:404-409, 1995. PMID: 7752868)

Mechanical Efficiency: Influence of Biological Sex



Elite male runners were ~10% more efficient and could hold a given pace at ~6 ml/kg/min lower O_2 cost

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Bassett & Howley, Med Sci Sports Exerc 2000. doi: 10.1097/00005768-200001000-00012.
(Based on: Daniels et al. Med Sci Sports Exerc 24:483-489, 1992. PMID: 1560747).

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Modeling: optimal marathon performance on the basis of physiological factors

marathon running speed

$$= \dot{V}O_{2\,max}\,(ml \cdot kg^{-1} \cdot min^{-1}) \times \%\dot{V}O_{2\,max} \text{ at LT} \times \text{RE}\,[km \cdot h^{-1} \cdot \dot{V}O_2^{-1}\,(ml \cdot kg^{-1} \cdot min^{-1})]$$

"The fastest time for the marathon predicted with this model is 1:57:58 in a hypothetical subject with a VO_{2max} of 84 ml/kg/min, a lactate threshold of 85% of VO_{2max}, and an exceptional running economy"

Joyner. J Appl Physiol 1991. doi: 10.1152/jappl.1991.70.2.683.

Eliud Kipchoge during his world record run at the 2022 Berlin marathon with 2:01:09

Image: https://en.wikipedia.org/wiki/Marathon_world_record_progression

RESEARCH ARTICLE

Physiological demands of running at 2-hour marathon race pace

Laboratory-based evaluation of 16 world-class male distance runners

"The mean O_2 cost for these athletes (n=7) was 191±19 mL/kg/km such that running at 21.1 km/h required an absolute VO_2 of ~4.0 L/min and represented 94±3% VO_2peak...

a sub 2-h marathon would require a 59 kg runner to sustain a VO_2 of ~67 mL/kg/min."

Jones et al. J Appl Physiol 2021. doi: 10.1152/japplphysiol.00647.2020.

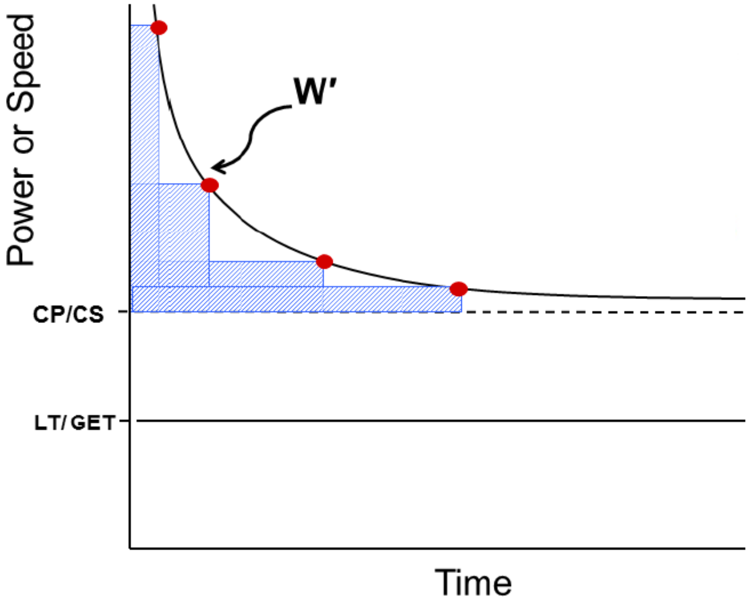
Mean performance speed or power

$$\text{Non-oxidative energy contribution} + (\text{Performance } \dot{V}O_2 \times \text{Economy or efficiency})$$

Jones et al. J Physiol 2023. doi: 10.1016/j.cell.2014.10.029.

Critical Power or Speed

“a ‘fatigue threshold’ (that) separates exercise intensity domains within which the physiological responses to exercise can (<CP) or cannot (>CP) be stabilized”



‘Sustainable’ work rate

Poole et al. Med Sci Sports Exerc 2016. doi:10.1249/MSS.0000000000000939.

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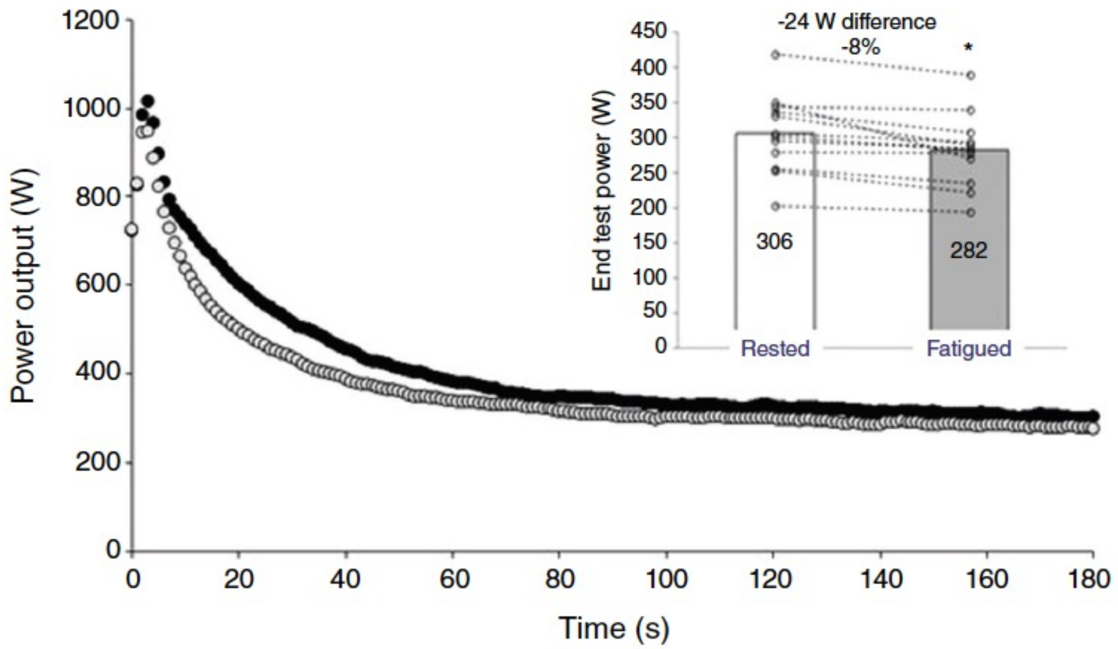
Critical Power or Speed

A dynamic variable with many influences including during prolonged exercise



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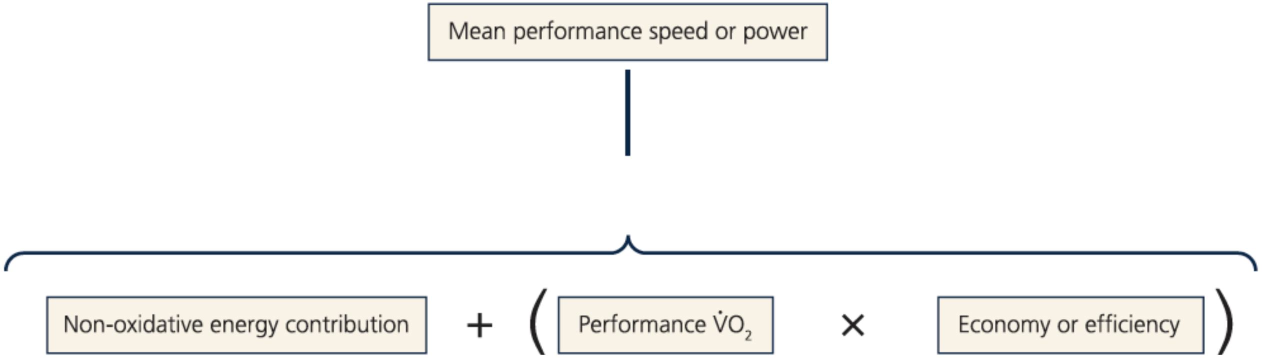
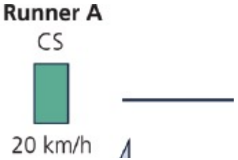
Jones et al. J Physiol 2023. doi: 10.1016/j.cell.2014.10.029.
Based on: Clark et al. Med Sci Sports Exerc 2018. doi: 10.1249/MSS.0000000000001601.



Jones et al. J Physiol 2023. doi: 10.1016/j.cell.2014.10.029.

The fourth dimension: physiological resilience as an independent determinant of endurance exercise performance



"The three physiological pillars (are) not static but prone to significant deterioration as fatiguing endurance exercise proceeds…

The mechanistic basis for such differences in fatigue resistance or 'physiological resilience' are not resolved.

Jones et al. J Physiol 2023. doi: 10.1016/j.cell.2014.10.029.

Take Home Points

1) Endurance performance is primarily determined by three factors: VO_{2max}, the fractional utilization of VO_{2max}, and exercise economy.

2) Identification of the highest sustainable oxidative metabolic rate (i.e. 'critical VO_2' or maximal metabolic steady state) is challenging.

3) Physiological resilience is a fourth dimension of performance that reflects the dynamic nature of the traditional determinants.

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Thank you!

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