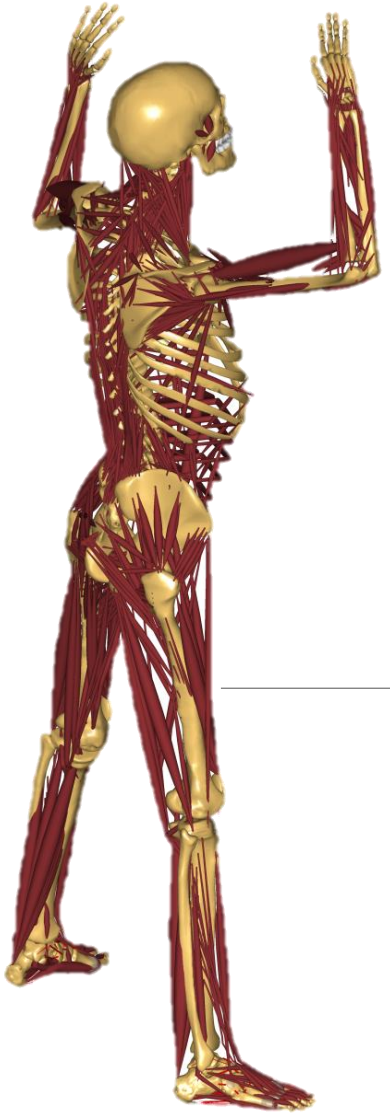
Metabolism Modeling in AnyBody



AN OVERVIEW

Contents

- Introduction: Overview of metabolism models in AnyBody
- Metabolic energy laws
  - Simple model based on efficiency
  - Models by Bhargava and Umberger
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Metabolic Power in AnyBody

- **AnyMetabModelSimple:** Simple metabolic law based of efficiency coefficients.
- **AnyMetabModelU:** Metabolic power model using the concepts by B.R.Umberger.
- **AnyMetabModelB:** Metabolic power model using the concepts by L.J.Bhargava.
- **AnyMetabModelBase** is metabolic power model base-class. It is abstract.
- **AnyMuscle** may have an **AnyMetabModel** to calculate metabolic power related quantities. If not it will use simple relationships like older versions of AnyBody (this is not recommended).
- **AnyBodyStudy** can set a default **AnyMetabModel.**

Metabolic Power based on efficiency.

From the study by Margaria, R.(1968)[1]

$$P_{met} = \frac{P_m}{e}, \text{ where } e = \begin{cases} e_{con} & \text{if } v^{ce} \leq 0 \\ e_{ecc} & \text{if } v^{ce} > 0 \end{cases}.$$

$e_{con} = 0.25$ and $e_{ecc} = -1.2$

[1] Margaria, R. (1968). Positive and negative work performances and their efficiencies in human locomotion. Internationale Zeitschrift für angewandte Physiologie einschließlich Arbeitsphysiologie, 25(4), 339-351.

Other relevant papers:

[2] Voigt, M., Bojsen-Møller, F., Simonsen, E. B., & Dyhre-Poulsen, P. (1995). The influence of tendon Young's modulus, dimensions and instantaneous moment arms on the efficiency of human movement. Journal of biomechanics, 28(3), 281-291.

[3] De Haan, A., Schenau, G. V. I., Ettema, G. J., Huijing, P. A., & Lodder, M. A. (1989). Efficiency of rat medial gastrocnemius muscle in contractions with and without an active prestretch. *Journal of Experimental Biology*, *141*(1), 327-341.

[4] Asmussen, E. (1953). Positive and negative muscular work. *Acta Physiol Scand*, *28*(4), 364-82.

Simple Model in AnyBody

- The **AnyMetabModelSimple** class comprises the simple metabolic power model using efficiency coefficients.
- This is also the model that AnyBody have used previously, and still uses as fall-back (but with $e_{con} = 0.25$ and $e_{ecc} = -1.25$)
- Parameter naming in AnyScript:
  - e_{con}: EtaCon
  - e_{ecc}: EtaEcc

Popular Metabolic Power Models

- Umberger et al. 2003[1] and 2010[2]
- Bhargava et al. 2004[3]
- Others (not in AnyBody)
  - Lichtwark and Wilson 2005[4]
  - Zarrugh et al. 1974[5]

[1] Umberger, B. R., Gerritsen, K. G., & Martin, P. E. (2003). A model of human muscle energy expenditure. *Computer methods in biomechanics and biomedical engineering*, *6*(2), 99-111.

[2] Umberger, B. R. (2010). Stance and swing phase costs in human walking. *Journal of the Royal Society Interface*, *7*(50), 1329-1340.

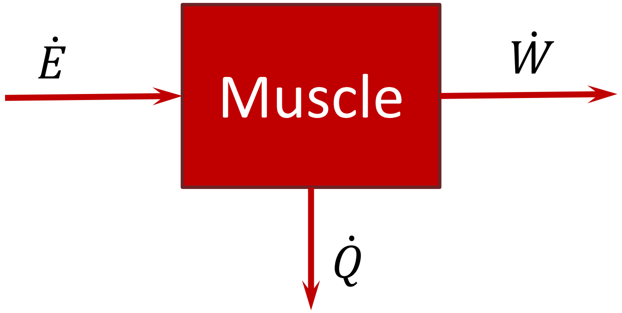
[3] Bhargava, L. J., Pandy, M. G., & Anderson, F. C. (2004). A phenomenological model for estimating metabolic energy consumption in muscle contraction. *Journal of Biomechanics*, *37*(1), 81-88.

[4] Lichtwark, G. A., & Wilson, A. M. (2005). A modified Hill muscle model that predicts muscle power output and efficiency during sinusoidal length changes. *Journal of Experimental Biology*, *208*(15), 2831-2843.

[5] Zarrugh, M. Y., Todd, F. N., & Ralston, H. J. (1974). Optimization of energy expenditure during level walking. *European Journal of Applied Physiology and Occupational Physiology*, *33*(4), 293-306.

Metabolic Power Entities

- 1st law of thermodynamics: $\dot{E} = \dot{Q} + \dot{W}$



$\dot{E}$: net metabolic energy rate input to the muscle (also called P_{met})

$\dot{Q}$: rate of muscle heat liberation

$\dot{W}$: power of the contractile element of the muscle (called P_m in AnyBody)

$\dot{H}$: heat rate produced by the muscle being active (not in AnyBody)

AnyBody recommendation (and Umberger2010 law)

$$\dot{Q} = \begin{cases} \dot{H}, & v_{CE} \le 0 \\ \dot{H} - \dot{W}, & v_{CE} > 0 \end{cases} \text{ and } \dot{E} = \begin{cases} \dot{H} + \dot{W}, & v_{CE} \le 0 \\ \dot{H}, & v_{CE} > 0 \end{cases}$$

Note that $v_{CE} = \dot{L}_{CE}$, i.e. positive for lengthening (eccentric work)

Umberger2003 and Bhargava2004 law

$$\dot{Q} = \dot{H} \text{ and } \dot{E} = \dot{H} + ?\,\dot{W}$$

This plus-sign is implemented as a parameter so you can add (+1.0, default), or subtract (-1.0), or even do fractions.

Note: this can lead to negative $\dot{E}$ for eccentric work (negative $\dot{W}$)

Heat rate by Bhargava et al. 2004:

$$\dot{H} = \dot{H}_A + \dot{H}_M + \dot{H}_S + \dot{H}_B$$

(Activation + Maintenance + Shortening/Lengthening + Basal) each in W

1) Activation heat rate

const.

$$\dot{H}_A = \phi_{df} m(F_{cfast} C_{A,fast} u_{fast} + F_{cslow} C_{A,slow} u_{slow})$$

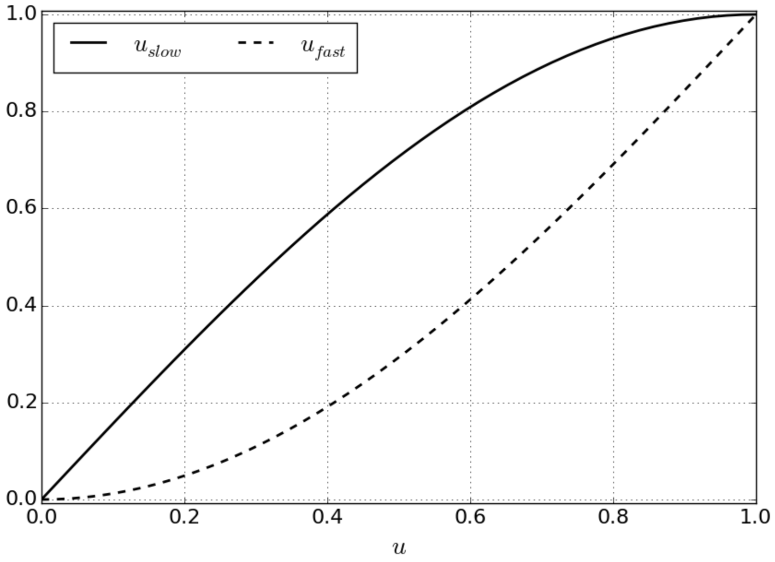
$$\phi_{df} = \phi_0 + e^{-t_{stim} u(t)/\tau_{df}}$$

Zero to model steady-state

Not in AnyBody

$$u_{fast}(t) = 1 - \cos\left[\frac{\pi}{2} u(t)\right]$$

$$u_{slow}(t) = \sin\left[\frac{\pi}{2} u(t)\right]$$



Bhargava's values:

$C_{A,fast}$, $C_{A,slow}$ are 133 W/kg and 40 W/kg.

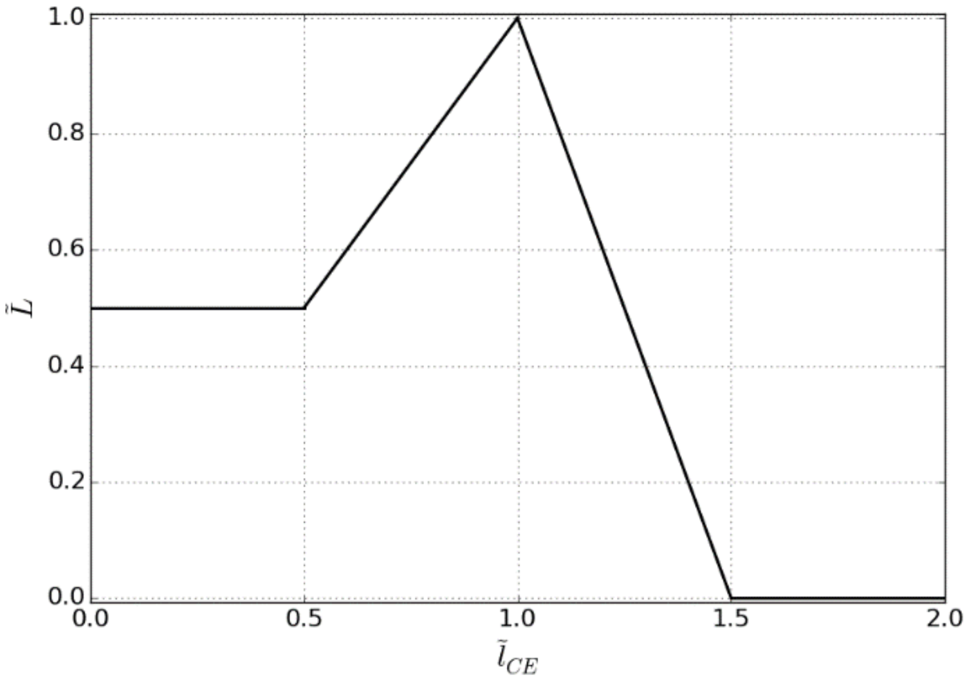
ϕ_0 is 0.06

Heat rate by Bhargava et al. 2004:

2) Maintenance heat rate

$$\dot{H}_M = \tilde{L}(\tilde{l}_{CE}) \cdot m(F_{cfast} C_{M,fast} u_{fast} + F_{cslow} C_{M,slow} u_{slow})$$

const.



$$\tilde{L}(\tilde{l}_{CE}) = \begin{cases} 0.5, & \tilde{l}_{CE} \leq 0.5 \\ \tilde{l}_{CE}, & 0.5 \leq \tilde{l}_{CE} \leq 1 \\ -2\tilde{l}_{CE} + 3, & 1 \leq \tilde{l}_{CE} \leq 1.5 \\ 0, & 1.5 \leq \tilde{l}_{CE} \end{cases}$$

Bhargava2004:
$C_{M,fast}$=111 W/kg
$C_{M,slow}$=74 W/kg

Heat rate by Bhargava et al. 2004:

3) Shortening/lengthening heat rate

$$\dot{H}_S = \begin{cases} -(C^{iso}_{\mathrm{SL},Con} F^{iso}_{CE} + C_{\mathrm{SL},Con} F_{CE}) v_{CE}, & v_{CE} \leq 0 \\ +C_{\mathrm{SL},Ecc} F_{CE} v_{CE}, & v_{CE} > 0 \end{cases}$$

F^{iso}_{CE}: muscle fiber isometric force (N)
F_{CE}: muscle fiber force (N)
v_{CE}: velocity of the contractile element (m/s)
$\dot{H}_S$: (W)

Bhargava2004:
$C^{iso}_{\mathrm{SL},Con}$=0.16
$C_{\mathrm{SL},Con}$=0.18
$C_{\mathrm{SL},Ecc}$=0.157

The red '+' is actually a minus in the paper, but it is assumed to be a typo as it may lead to negative $\dot{H}_S$. Obtain orig. paper formula entering a negative $C_{SL,Ecc}$

4) Basal heat rate

Heat rate for resting skeletal muscle at 0°C:

$\dot{H}_B = mC_B$

Bhargava2004: $C_B = 0.0225$ W/kg.

Bhargava Model in AnyBody

- The **AnyMetabModelB** class comprises the model by Bhargava2004 using the paper's values as default values for optional parameters.

- Parameter naming in AnyScript:
  - ϕ_0: CoefActPowerPhi0
  - $C_{A,slow}$: CoefActPowerSlow
  - $C_{A,fast}$: CoefActPowerFast
  - $C_{M,slow}$: CoefMaintPowerSlow
  - $C_{M,fast}$: CoefMaintPowerFast
  - $C_{\mathrm{SL},Con}^{iso}$: CoefSLPowerConIso
  - $C_{\mathrm{SL},Con}$: CoefSLPowerCon
  - $C_{\mathrm{SL},Ecc}$: CoefSLPowerEcc
  - C_B: CoefBasalPower
  - MuscleDensity
  - AddMusclePowerForEcc (a On-Off switch for controlling concept cf. slide "Metabolic Power Entities").
  - A coefficient called 'AddMusclePowerForEccCoef' (default=1.0) controls how much muscle power is added for the eccentric case. For instance use -1.0 to subtract the muscle power. See intro slide.

Heat rate by Umberger et al. 2003, 2010

$$\dot{H} = m\dot{h}$$

with $\dot{h} = \dot{h}_A + \dot{h}_M + \dot{h}_S$

(Activation + Maintenance + Shortening/Lengthening) each in W/kg

1) Activation/Maintenance Heat Rate

$\dot{h}_A$ and $\dot{h}_M$ are considered together

$$\dot{h}_A + \dot{h}_M = \begin{cases} C_{AM} a_h^{0.6} C_{AM}^{aer}, & l_{CE} \leq \overline{L_f} \\ C_{AM} a_h^{0.6} C_{AM}^{aer} (0.4 + 0.6 f_{CE}^{iso}), & l_{CE} > \overline{L_f} \end{cases}$$

$C_{AM} = C_{AM,fast} F_{cfast} + C_{AM,slow}$: activation/maintenance heat rate constant in W/kg.

Umberger2003/2010:
$C_{AM,slow} = 25$
$C_{AM,fast} = 128$
C_{AM}^{aer}=1.0..1.5

Heat rate by Umberger et al. 2003, 2010

2) Shortening/Lengthening Heat Rate

$$\dot{h}_{SL} = C_{AM}^{iso}\,\tilde{v}_{CE} C_{AM}^{aer} \alpha_{SL} \quad \text{where } C_{AM}^{iso} = \begin{cases} 1, & l_{CE} \leq \bar{L}_f \} \\ f_{CE}^{iso}, & l_{CE} > \bar{L}_f \end{cases}$$

$$\text{and } \alpha_{SL} = \begin{cases} -a_{\dot{h}}^{2.0}(\alpha_{S,ST} F_{cslow} + \alpha_{S,FT} F_{cfast}), & \tilde{v}_{CE} \leq 0 \\ a_{\dot{h}} \alpha_L, & \tilde{v}_{CE} > 0 \end{cases}$$

Shortening/lengthening coefficients:

$$\alpha_{S,ST} = \frac{4C_{AM,slow}}{\tilde{v}_{CE}^{\max,ST}}, \alpha_{S,FT} = \frac{C_{AM,slow}+C_{AM,fast}}{\tilde{v}_{CE}^{\max,FT}}, \alpha_L = C_{SL,Ecc}\alpha_{S,ST}$$

$C_{SL,Ecc} = 0.3$ (Umberger 2010)

f_{CE}^{iso}: normalized isometric force of the contractile element

Notice:

$\tilde{v}_{CE} = v_{CE}/\bar{L}_f$, i.e. normalized contractile element velocity

But when we insert in $\dot{h}_{SL}$, $\bar{L}_f$ cancels out from $\tilde{v}_{CE}$ and $\tilde{v}_{CE}^{\max,i}$ in the denominator of all terms of α_{SL}.

Umberger Model in AnyBody

- The **AnyMetabModelU** class comprises the model by Umberger2010 using the paper's values as default values for optional parameters. The Umberger2003 model can be realized by parameters

- Parameter naming in AnyScript:
  - $C_{AM,slow}$: CoefActMaintPowerSlow
  - $C_{AM,fast}$: CoefActMaintPowerFast
  - C_{AM}^{aer}: CoefActMaintPowerAer
  - $C_{SL,\mathrm{Ecc}}$: CoefSLPowerEcc
  - MuscleDensity
  - AddMusclePowerForEcc (a On-Off switch for controlling concept cf. slide "Metabolic Power Entities")
  - A coefficient called 'AddMusclePowerForEccCoef' (default=1.0) controls how much muscle power is added for the eccentric case. For instance use -1.0 to subtract the muscle power. See intro slide.

Closing remarks

- Some studies show that the even the simple model can provide good absolute values for musculoskeletal simulation, while more advanced models may capture some trends better.
- Umberger (2010) model includes
  - Nonlinear scale of submaximal activations
  - Correction on the definition of the metabolic energy rate compared to the 2003 version
- Bhargava model is a nice model, but it is using a definition of $\dot{E} = \dot{H} + \dot{W}$ for the metabolic rate. Therefore, if the updated definition is desired to use, recalibration of the parameters for the shortening/lengthening term seems necessary.
- Possibility for negative Pmet (non-physiological) by Umberger (2003) and Bhargava has been eliminated (optional) in AnyBody.
- Mathematical models, validation and tuning of parameters is a topic of more research.

Known issues

- Muscle with zero volume leads to zero muscle mass. This implies that some terms in e.g. AnyMetabModelB and AnyMetabModelU are neglected. Pay attention to the error messages.
- Muscle with poor fiber length specification (e.g. zero optimal fiber-length such as simple muscle models) requires modifications because of normalization problems.
  - Zero optimal fiber length, AnyMetabModelB assumes optimal fiber-length at all muscle positions/lengths.
  - For zero max contraction velocities (e.g. from zero optimal fiber length), AnyMetabModelU neglects shortening-lengthening terms
- Some models include "virtual muscles", i.e. actuators that are not real muscles but are made as AnyMuscle object in order for them to enter the Muscle Recruitment. These are also included in the Pmet calculations, even though they may not be physiological muscles. In coming versions, such actuators can be modelled AnyRecruitedActuator. They can also be equipped with an AnyMetabModelSimple with parameters providing zero Pmet.