Metabolic Consumption

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| **Activity** | **Summary** | **Link** |
| Walking | * Experimental measurements   + **“Indirect calorimetry” - pulmonary gas exchange rates, VO2**   + Force plates for GRFs   + Motion capture   + EMG data? * Calculations: **7 metabolic energy models** (from other lit) | <https://www.biorxiv.org/content/10.1101/588590v2.full#disp-formula-1> |
| Running | * Stanford paper (Delp’s group) * OpenSim muscle-generate simulations used to see metabolic power consumption * Instantaneous metabolic power consumed was predicted based on “**muscle energetics model**”   + Integrated for total consumption | <https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0163417#sec001> |
| Walking | * Stanford paper (Delp’s group) * Metabolics models with **OpenSim** software * Collected activity of muscles with EMG, GRFs, motion tracking * “estimat[ed] whole-body metabolic energy consumption using indirect calorimetry” * “CMC solves for muscle excitations” * **Compared metabolics model to indirect calorimetry** * “Metabolic rate attributed to joint motions”   We invite other researchers to use our data and code (freely available at <https://simtk.org/home/assistloadwalk>) to build upon our work | [Simulating ideal assistive devices to reduce the metabolic cost of walking with heavy loads](https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0180320) |
| Walking | * Stanford (Collins) paper * “Metabolic rate was estimated using **indirect calorimetry**. Volumetric oxygen” | <https://journals.physiology.org/doi/full/10.1152/japplphysiol.01133.2014> |
| Running | * Stanford (Uchida/Delp) * **Metabolics models with OpenSim** software * *“performed muscle-driven simulations of running... and computed the average metabolic power consumed by each muscle”* * “ CMC simulation results were used as inputs to a modified version of the muscle energetics model proposed by Umberger et al.;” | [Stretching Your Energetic Budget: How Tendon Compliance Affects the Metabolic Cost of Running](https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0150378) |
| Running | Delp paper with **model for muscle energetics** | <https://www.sciencedirect.com/science/article/pii/S0021929012006768?via%3Dihub> |
| All movements | * “**Muscle Energy Expenditure Model**: Following the traditional approach of partitioning muscle energy liberation, the total rate of muscle energy expenditure” * “**Total Energy Rate**: The total rate of energy liberation for a muscle in Wkg-t total muscle mass is obtained from the following equation” | [A Model of Human Muscle Energy Expenditure: Computer Methods in Biomechanics and Biomedical Engineering: Vol 6, No 2](https://doi.org/10.1080/1025584031000091678) |
| Cycling | * Measured: “expired gasses, kinematics, and EMG from 7 lower limb muscles” (purpose PDF p14) * Muscle activation found through EMG, force plate pedals, computational modeling * Used modified **OpenSim BothLegs.oism** file * Lit review section: O2 consumption & lactate threshold (p23), mechanical output (p24) * “Alterations in posture influence muscle mechanics such as muscle lengths, lever arms, and shortening velocity.” (p24) **\*mentions seat height** * Upright posture is good for power output but not good for **wind resistance**…” (p25) * **Activated muscles** (p28) -- high variation   + Computational modeling of (p30-31) * Computational/MS modeling (including/favoring OpenSim) (p31-38) * Research article starts on p50   + \*recommended **knee angle** (p52, p24)   + \*\*\* p53 * *Seems like a very similar application, just a different geometry parameter changed* * *Paper talks about metabolic efficiency but seems more steeped in kinematic efficiency?* | [https://studylib.net/doc/10914524/the-effects-of-cleat-placement-on-muscle-mechanics-and-me…](https://studylib.net/doc/10914524/the-effects-of-cleat-placement-on-muscle-mechanics-and-me%E2%80%A6)  PDF [Master’s Thesis: “The Effects Of Cleat Placement On Muscle Mechanics And Metabolic Efficiency In Prolonged Sub-maximal Cycling”](https://drive.google.com/file/d/1neVWFllAfwIThxMLbOcF9uPtFlwAbv8P/view?usp=sharing) |
| Cycling | * Used OpenSim * Master’s Thesis Title: Inverse Dynamic Analysis of ACL Reconstructed Knee Joint Biomechanics During Gait and Cycling Using OpenSim * Not much wrt metabolic analysis * Kinematic data collected with motion tracking → fed into OpenSim for Inverse Kinematics (IK) → RRA * Kinetic force plate GRF/EMG data → CMC in OpenSim | [Article](https://digitalcommons.calpoly.edu/cgi/viewcontent.cgi?article=3402&context=theses) |
| All/ Cycling | * Metabolic heat production (muscle metabolism) → rise in body temp → critical body temp of 40C after which “exercise is limited” * Chemical reactions (ATP, etc.) | <https://link.springer.com/article/10.2165/00007256-200535100-00004> |
| Muscle Expenditure Model | * Total rate of muscle energy expenditure = activation heat rate + the maintenance heat rate +shortening/lengthening heat rate + mechanical work rate of the CE * Hill-type muscle model * *“Use of the ...model of muscle energy expenditure in conjunction with forward dynamic computer simulations should allow for a more complete understanding ...”* | <https://www.tandfonline.com/doi/pdf/10.1080/1025584031000091678?needAccess=true> |

Bike Biomechanics

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| **Activity** | **Summary** | **Link** |
| Cycling | * Setting angle constraints on 8 main leg muscles used while biking * Deriving angular position, velocity, and acceleration equations as a function of body part length and bike dimensions * Power = moment \* angular velocity | [A method for biomechanical analysis of bicycle pedalling](https://www.sciencedirect.com/science/article/pii/0021929085900193) |
| Cycling | * Page 201 gives another graphic explaining/confirming the muscle groups used while biking, along with the crank angles at which they are activated * Some saddle height discussions and effect on certain muscle groups (page 202-203) * Explain that muscle activation on uphill biking has yet to be explored (could be an interesting avenue eventually) | [(PDF) Biomechanics of Cycling](https://www.researchgate.net/publication/269514219_Biomechanics_of_Cycling) |
| Cycling | * Using loose percentages to describe the effect of raising/lower saddle height on overall performance and efficiency (page 471) * “The range of 25–30 of knee flexion has been advocated to reduce the risk of knee injuries and minimize VO2.“ | [(PDF) Effects of Bicycle Saddle Height on Knee Injury Risk and Cycling Performance](https://www.researchgate.net/publication/51167758_Effects_of_Bicycle_Saddle_Height_on_Knee_Injury_Risk_and_Cycling_Performance) |
| Cycling | * Another perspective on how to calculate moments and power using mechanics * Equations look similar to my first link but I’ll need to dive deeper | [Multivariable optimization of cycling biomechanics](https://www.sciencedirect.com/science/article/pii/0021929089902170) |
| Cycling | * Interesting literature review for some more breadth on the topic * “One method to determine optimal seat height is 109 percent of the cyclist's inseam leg length measurement” * Discusses pedaling rate as one of the considerations towards efficiency | [Cycling Biomechanics: A Literature Review](https://www.jospt.org/doi/pdf/10.2519/jospt.1991.14.3.106) |
| Cycling | * Goniometric evaluation:   + knee angle: 25-35 degrees * Anthropometric evaluation:   + inseam length: saddle height should be 109% of inseam length * Dynamic evaluation:   + lateral pelvic tilt increases knee flexion by 5-6 degrees   + hamstring length changes as saddle height changes and so hamstring flexibility influences ideal saddle height   + knee flexion angle of 30-40 degrees is ideal for dynamic movement * “findings confirm the suggestion of other authors (4,10,13) that hip and knee joints are sensitive to saddle height changes. Contrary to other studies, saddle height changes did not show any influence on ankle kinematics” | [INFLUENCE OF SADDLE HEIGHT ON LOWER LIMB](https://drive.google.com/file/d/167pmO2C6aYsp8FrdNE8syndT-VJQxtyP/view?usp=sharing)  [KINEMATICS INWELL-TRAINED CYCLISTS: STATIC VS.](https://drive.google.com/file/d/167pmO2C6aYsp8FrdNE8syndT-VJQxtyP/view?usp=sharing)  [DYNAMIC EVALUATION IN BIKE FITTING](https://drive.google.com/file/d/167pmO2C6aYsp8FrdNE8syndT-VJQxtyP/view?usp=sharing) |
| Cycling | * compared saddle height adjustment impact using 25 degree knee angle, 35 degree knee angle, and 109% of inseam length   + 25 degree knee angle is more economical, ie lower metabolic cost at a fixed submaximal work rate.   + 25 degree knee angle based saddle height also results in lower rating of perceived exhaustion, which could imply increased power output and therefore, higher efficiency | [EFFECTS OF SADDLE HEIGHT ON ECONOMY AND ANAEROBIC POWER IN WELL TRAINED CYCLISTS](https://drive.google.com/file/d/1epHiJH4W4rnFERT56a-k01aJaHJ48m_Y/view?usp=sharing) |
| Range of Motion | * Paper studies the utilization of range of motion at the hip, knee, and ankle joints during exercise on a bicycle * “mean hip range of motion (ROM) during normal cycling was 38° ranging from 32–70 hip flexion” * “mean knee ROM was 66° ranging from 46–112° knee flexion” * “ankle ROM was 24° ranging from 2° plantarflexion to 22° dorsiflexion” * “different pedaling rates did not significantly change the lower limb joint motions” | [Joint Motions of the Lower Limb during](https://drive.google.com/file/d/1V8PaI9ImMaIQHJGNmiH1SVkz6u3ZPGgB/view?usp=sharing)  [Ergometer Cycling](https://drive.google.com/file/d/1V8PaI9ImMaIQHJGNmiH1SVkz6u3ZPGgB/view?usp=sharing) |
| Joint Angles | * Paper studies effect of saddle height, pedaling cadence & workload on Joint Kinematics during cycling of non-cyclists * Outputs for work on each joint are measured via force data from WINDAQ acquisition system * Sagittal kinematics were acquired by single camera perpendicular to movement plane * Linear and angular velocities and accelerations were computed from joint position and pedal force data * Inverse dynamics was used to calculate net joint moment and resultant forces at hip, knee and ankle * Joint power was calculated by product of net joint moments and angular velocity | [Effects of Saddle Height, Pedaling Cadence, and Workload on Joint Kinetics and Kinematics During Cycling](https://drive.google.com/file/d/1xL8P2MSacA1WRg6TSBh_CftqxvdzTC7v/view?usp=sharing) |
| Joint angles | Knee angle is several planes measured via calibrated sensor | Estimation of 3D knee joint Angles during Cycling using Inertial Sensors |
| Muscle Activation Period | The study measured activation period of lower limb muscles during cycling in different saddle positions.  Study does not have high power (Only 3 elite cyclists in the study), but gives some sort of reference point for activation time as a percent of total. | Assessment of the effect of saddle position on cyclists’ pedaling technique |
| Cycling | One leg and two leg pedalling experiment to calculate total work as a function of metabolic output | <https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.895.1581&rep=rep1&type=pdf> |
| Cycling | 3 different rider orientations to output normal+shear force on the pedals | Forces applied to a bicycle during normal cycling |
| Cycling | Used a very similar biomechanics modeling tool to OpenSim (with forward dynamics and inverse dynamics) to output crank torque as function of crank angle | Prediction of crank torque and pedal angle profiles  during pedaling movements by biomechanical optimization |
| Cycling | Calculating effective force on bike pedals with a series of analytical equations and using experimentation to verify | Visualization of pedaling technique using cleat-size biaxial load cells |
| Cycling | 11 subject trial to determine average pedal forces (normal, shear, resultant) with varying power inputs (75%, 90%, 100%) | Pedal force effectiveness in cycling: A review of constraints and training effects |

OpenSim Resources

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| **Activity** | **Summary** | **Link** |
| Cycling model for OpenSim | * They don’t offer their original model but roughly describe how they made their own cyclist based on OpenSim’s whole body running model. * Gait2393 is ideal for modeling pedaling motion, but RoadOne is the model they developed on their own (using full body running model) | [2 thoughts on “Overview of OpenSim Models”](https://hammondcycling.com/overview-of-opensim-models/) |
| ^^ | * Students from ME 485 developed an “educational cycling model” * Important note - the students only modeled one leg for the pedaling motion (hmmm)      * “We would like to acknowledge Ajay Seth who provided the original cycling model and offered value feedback on model simplification. “ -> we might want to reach out to this Mr. Ajay Seth 👀 | [OpenSim Teaching Materials -- Educational Cycling Mode](https://simtk-confluence.stanford.edu/display/OpenSim/OpenSim+Teaching+Materials+--+Educational+Cycling+Model)  [https://simtk.org/docman/?group\_id=1529l](https://simtk.org/docman/?group_id=1529) |
| List of general models | * Several base models that we could probably adapt with a little guidance from Scott | <https://simtk-confluence.stanford.edu/display/OpenSim/Musculoskeletal+Models> |
| Tips and tricks | * This could be useful depending on how much groundwork we are doing for the model...but it is an hour long so I will watch it later... | <https://www.youtube.com/watch?v=ZG7wzvQC6eU> |
| Metabolic Cost OpenSim Tutorial | * Metabolic cost data plotted after running CMC tool   + During CMC run, a ProbeReporter analysis runs to calculate metabolic rates for each muscle requested (need to ask Scott how to set up since tutorial has pre-loaded CMC startup files) | <https://simtk-confluence.stanford.edu:8443/display/OpenSim/Simulation-Based+Design+to+Reduce+Metabolic+Cost> |
| Fatigue Muscle Models | * ME485 project about fatigable muscle models | <https://simtk-confluence.stanford.edu/display/OpenSim/Design+of+a+Fatigable+Muscle> |

References from ME485 cycling project:

* Citterio and Agostoni (1984). Selective Activation of Quadriceps Muscle fibers According to Bicycling Rate. American Physiological Society.
* Kautz and Hull (1993). A Theoretical Basis for Interpreting The Force Applied to the Pedal in Cycling. Journal of Biomechanics. Vol 26 No2, pp 155-165.
* Raasch et al. (1997). Muscle Coordination of Maximum Speed Pedalling. Journal of Biomechanics. Vol 30, pp 595.
* Thelen, Anderson, and Scott (2002). Generating dynamic simulations of movement using computed muscle control. Journal of Biomechanics. Vol 36, pp 321-328.

Biological/ Biomechanical

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| Fast vs slow twitch fibers | * **Fast(Type II)** -- more powerful/shorter forces, shorter durations, fatigue quickly   + **For sprinting, including sprint cyclists** * **Slow (Type I)** -- fatigue-resistant. smaller, sustained movements   + **For endurance, including cycling** * All muscles are a combo of both types of fibers * Differs based on age, training, biology, etc * **OpenSim text file required for addMetabolicProbles.py → declare % fast vs slow twitch** | <https://blog.nasm.org/fitness/fast-twitch-vs-slow-twitch> |
| Fibers & efficiency in cycling | * ST/ FT fibers vs cycling efficiency * “The purpose … was to find out if contracting muscle, predominantly ST fibers or predominantly FT fibers, performed differently in the long run during bicycle...” * Efficiency quantified via VO2max * Results also have to do with cycling rpm | <https://journals.physiology.org/doi/pdf/10.1152/jappl.1979.47.2.263> |
|  | Factors that make a difference that can be altered for specific riders, but can be documented for Specialized to alter:   * Muscle insertion points * % FT/ST for each muscle * Muscle PCSA * Overall body height, body weight, etc * Specific body length, weight dimensions * Rotation angles? |  |
| Muscle fibers & optimal cadences | * **“muscle fiber type distribution was ... important determinant of the energetics of pedaling”** * “Energy expenditure and the energetically optimal cadence were found to be higher in a model with more FT fibers than a model with more ST fibers, consistent with predictions from the experimental literature.” * “At the muscle level, mechanical efficiency was lower in the model with a greater proportion of FT fibers, but peaked at a higher cadence than in the ST model” * **“The differences in submaximal energy expenditure between subjects, and the cadences at which energy is minimized can presumably be explained largely by muscle fiber type distribution.”** * Hill-type muscle model * **Table 1** gives good muscle anthropometric data * **Table 2** gives good muscle FT/ST data * Models run for pedaling cadences of 40,60,80,100,120 rev/min * Muscle excitation patterns found w dynamic opti \* EMG was collected from 1 subject (closely matched) * Energetically optimal cadences (FT 64 rev/min; ST 55 rev/min) * \*\*\* Fig 5, Muscle mechanical efficiency vs cadence → much different for ST vs FT * Fig 4, “Whole-body energy expenditure, on the other hand, increased steadily from 60 to 120 rev min” different pattern than just lower leg energetics”   + BUT “suggests muscles operate on the plateau of the efficiency-cadence curve during cycling, with only extreme cadences leading to substantial penalties in efficiency: | [Muscle fiber type effects on energetically optimal cadences in cycling (PDF)](https://drive.google.com/drive/u/1/folders/1Sx8uDcjutgpDQeoHL4KC6jkfePjvI-68) |