Pumping Without Pedaling: How Corners Turn Timing into Speed

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Watch a skilled rider enter a berm: they arrive tall, compress as the turn loads up, and rise on exit - no pedaling, yet they launch out faster. This isn't magic; it's timing that lets the ground do positive work on you. This reciprocal motion between the bike and the rider is called pumping, evident in three places: rollers, banked corners (berms), and jumps. This article focuses on the physics in berms and a recent model by Golembiewski and colleagues that computes an optimal pumping rhythm through corners. We finish with brief notes on extending the same logic to rollers and jumps.

https://www.pinkbike.com/news/2024-qualifier-events-announced-for-uci-pump-track-world-championships.html

(Velosolutions Global, 2024)

The Basic Physics in a Berm

The turn is already bending your path toward the center, so the ground must push hard on the bike. That “heaviness” is the **normal load** N. A compact way to sketch the load you feel (or the “heaviness”) is:

$$N \approx M \cdot g \cdot cos(\beta) \ + \ M \cdot \frac{v^2}{R} \ + \ M \cdot a_n^{rider}$$

The first term is gravity on a bank with tilt β , the second term is the centripetal demand of the turn (speed v, radius R), and the third term is what **you** add by moving your body **normal** to the surface (a rider)a: positive when you compress, negative when you unweight). Even if the radius R stays roughly constant through the main arc, N **ramps up** when you go from straight to arc (entry) and **drops** when you go from arc back to straight (exit). Those ramps are the windows that matter.

You gain speed only when a sliver of the ground’s reaction force points **forward** along the bikes path (T). The instantaneous power is roughly P=Tv

During **entry/early arc**, the contact geometry naturally tilts a tiny piece of the big normal load forward. If you **compress right then** (make an(rider)>0), you briefly raise N when that tilt helps to push the bike forward, so T>0 and P>0: you’re doing **positive work** on the system—like pushing a swing at the right moment. Near **exit**, the load is falling; pressing now would tilt a component **backward** and do **negative work**. So you **stay low** through the end of the arc and **re-extend on the straight**, where unweighting won’t be turned into braking.

Two wheels = two chances. The timing simply splits across contacts: a short **bar press** as the **front** hits the entry ramp, then a short **pedal press** as the **rear** reaches it. Those two brief pulses create two small forward pushes per berm. Note that this isn’t conservation of angular momentum (mvr) because the ground is doing external work but applying compressive forces at the right time.

Why this matters. This turns “pump the berm” from a vibe into a **repeatable rule** you can coach, measure, and design for: press twice in the entry window, glide out, and you bank real, compounding speed—no pedaling required.

Inside the Research: A Two-Mass Model on a Banked Ribbon

The paper starts with a cartoon model (their **Fig. 1**) where the **bike** and the **rider** are represented by two points—centers of mass x^b and x^r—joined by a **massless link** of length $l(t)$ (Golembiewski et al., 2023, Section 3.2).

Fig. 1: Conceptual bike rider model

To give these points a world to live in, they build a 3D **banked surface**, called S, using a set of parametric equations ϕ

$$g : \mathbb{U} \to S, \quad g(\phi, \theta) = \begin{bmatrix} (R + r\cos\theta)\cos\phi \\ (\lambda R + r\cos\theta)\sin\phi \\ r(1 - \sin\theta) \end{bmatrix}$$

Think of g as a recipe that turns the pair "where you are around the track" (ϕ) and "where you are across the bank" (θ)into a 3-D position. Rather than let the bike wander anywhere on S, the authors **choose a riding line** by prescribing θ as a function of ϕ:ϕ

$$\theta^p(\phi) = \frac{\pi}{2}\cos^2\phi$$

Subsequently, the author derives a position equation for the bike–rider system that depends only on φ—the progress angle around the banked turn—under the riding line assumption that the rider holds an inner line on the straights and shifts toward the outer (higher) line near the apex.

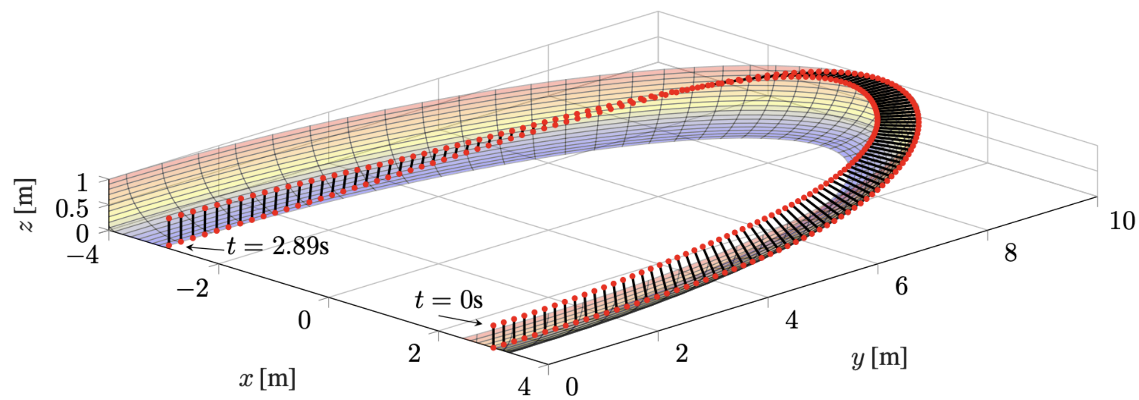


Fig. 7: Visualization of position within first curve

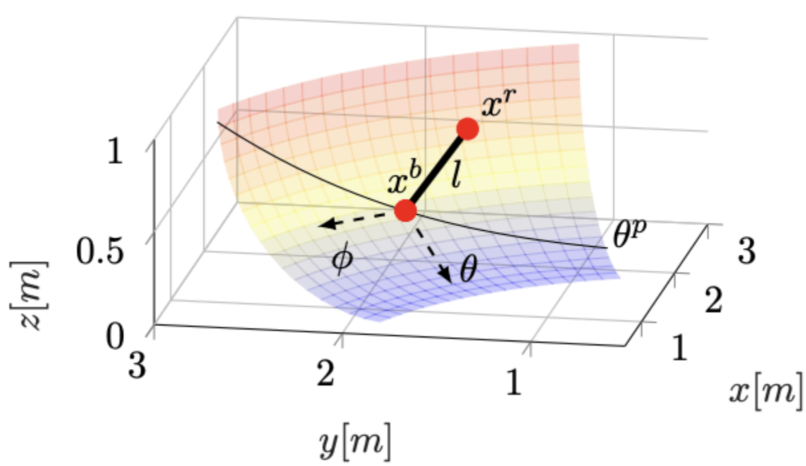


Fig. 2: Two-mass model on torus surface

To simplify the problem, the author also introduces an **upright constraint** (Fig. 2 c): this means the imaginary line between the bike and the rider is always perpendicular to the track surface. **The movement of the rider will only be orthogonally, n**o fore–aft lean—so $l(t)$is exactly "how much you squat or extend" relative to the bank. Under that constraint, an explicit expression for the **rider position** $(\widetilde{g})$ is derived.

$$x^r = \tilde{g}(\phi, l) = \begin{bmatrix} (R + r\cos\theta^p - l\cos\theta^p)\cos\phi \\ (\lambda R + r\cos\theta^p - l\cos\theta^p)\sin\phi \\ r(1 - \sin\theta^p) + l\sin\theta^p \end{bmatrix}.$$

This equation takes φ—the progress angle around the banked turn as input and l (the distance between the bike's COM and the rider's COM) as input, and outputs a point in 3D space.

Inside the Research: Setting up an equation of motion:

The author then explores the aspects considering motion, for example the velocity of the bike rider can be expressed as the time derivative of its position equation, indicated as $\dot{x}(t)$, and the acceleration between the bike and the rider can be expressed as the time derivative of l, indicate as $\ddot{l}$. In the real world, this means how quickly you **accelerate** your squat/extend. THe variable $\ddot{l}$ is the core of this investigation, as it becomes the control variable of our mathematical simulation.

From the position equation the author then computes **speeds** and **heights** for each mass. That gives:

- total **kinetic energy** K(one term for the bike, one for the rider),
- total **potential energy** U(gravity acting on each mass via its z-height).

Rather than list every force separately, they use the standard energy recipe to obtain **one equation that governs progress around the track**. Written in the compact form used in the paper, it's an **implicit Ordinary differential equation (ODE)** in ϕ (the angle of along-track motion) that also depends on your body motion:

$$0 \;=\; M(\phi, l)\,\ddot{\phi} \;+\; F(\phi, l)\,\dot{\phi}^2 \;+\; Q(\phi, l, \dot{l})\,\dot{\phi} \;+\; P(\phi, l, \dot{l}, \ddot{l})$$

The terms in this ODE are basically

- $M(\phi, l)\,\ddot{\phi}$: "inertia" for turning the system around the track.
- $F(\phi, l)\,\dot{\phi}^2$: curvature/banking terms that grow with speed.
- $Q(\phi, l, \dot{l})\,\dot{\phi}$: coupling between your **height change** and forward motion.
- $P(\phi, l, \dot{l}, \ddot{l})$: the piece that captures **your deliberate squat/extend acceleration** $\ddot{l}$ (the "pump").

Intuition: when you **accelerate your body along the surface normal** ($\ddot{l}$ not zero) while the contact frame is oriented by the berm, that last term acts like a **forward push** in the along-track equation. That's the mechanism the model quantifies.

Setting up an optimal control problem

The paper asks a simple question: If you're not allowed to pedal, how should you squat and extend to get through a banked turn the fastest? To answer it, they turn riding into a small decision-making problem a computer can solve. This is called an optimal control problem.

$$\min_{u(\cdot)\in PC([0,T],\mathbb{R})} \int_0^T q^\top x + u^2\, dt \tag{4a}$$

$$\text{subject to} \quad \forall t \in [0,T]$$

$$0 = f(\dot{x}, x, u), \quad x(0) = x_0 \tag{4b}$$

$$x(t) \in \mathbb{X} \subseteq \mathbb{R}^4 \tag{4c}$$

$$u(t) \in \mathbb{U} \subseteq \mathbb{R}. \tag{4d}$$

State

Within the integral, x is a state vector: which stores four numbers at every instance:

- **Where you are around the corner** (an angle, call it ϕ).
- **How fast you are sweeping around** (the rate $\dot{\phi}$; faster rate = higher speed).
- **How tall you are above the bike along the banked surface** (the body–bike separation l).
- **How quickly that height is changing** ($\dot{l}$; going up or down).

The researchers bundle this into a little box that the computer updates over time which simulates the entire progress of the rider going around the track.

$$x(t) = [\phi,\ \dot{\phi},\ l,\ \dot{l}]^{T}$$

Reward and Punishments:

The term q is a weight vector, creating a **linear reward/penalty** on the state vector x. In the paper q=[−65,−65,0,0]. The terms are negative because we are trying to minimize the entire integrand, and the more negative the terms are the smaller the integrand gets. This rewards a bigger ϕ, $\dot{\phi}$, namely encouraging the virtual rider to ride farther and faster. The penalization is the term u^2. Here, u is the acceleration of the rider with respect to the bike, or pumping motion. If the rider inputs sudden pumping motions, u^2 raises quadratically, which makes the integrand larger, so the ocp is trying to encourage smooth motions. This translates to the real world as you are trying to preserve energy and stay in the humanly limits of motion.

Control (what you choose):

Your single choice is how hard you accelerate your body up or down relative to the bike, along the bank's normal direction. That's the essence of pumping:

- Positive control = compress (drive yourself down).
- Negative control = unweight (pop up).

They call this input $u(t) = \ddot{l}(t)$. Think of it as a knob that tells your virtual rider when to push and when to lighten.

The statement U(·) ∈ PC([0,T],R) just means the signal needs to be mostly smooth over the entire time simulated.

Dynamics constraint:

The model provides an equation that ties together how x changes when you choose u given the initial condition $x(0) = x_0$

The equation

$$0 = f(\dot{x}, x, u)\ ,\ x(0) = x_0$$

is derived from the earlier langragian, and makes sure the bike and the rider obeys physics:

This basically means: Given the track shape and gravity, if you push this hard right now, here's how your position, speed, and body height will evolve next.

The solver enforces this rule at every tiny time step so it never "cheats."

The integrand has "cost per second"; integrating over dt gives a **total cost**. Lower J means: you got **farther/faster** through the corner while using **less harsh acceleration**.

Setting realistic constraints

The researchers then determine the realistic bounds for length between the bike and rider and acceleration between the bike and rider by doing a motion capture of a real setup.

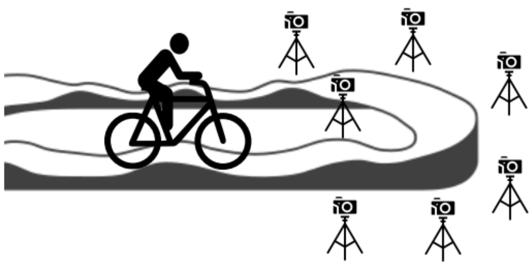


Fig. 3: Experimental setup

Fig. 4: Camera image with marked calculation points

They use motion trackers to track 46 markers at 100 Hz and infer rider CoM and bike reference points to measure what a human can actually do. The result were the graphs below:

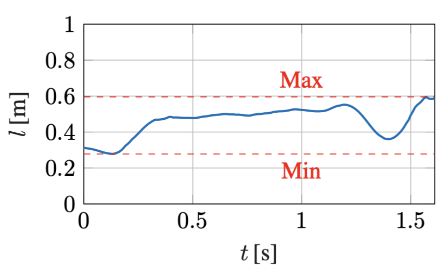


Fig. 5: Absolute distance between CoM rider and bike down tube

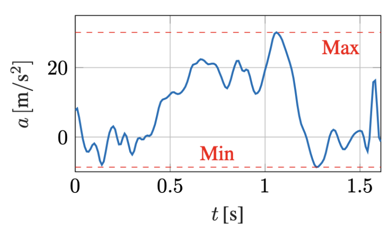


Fig. 6: Acceleration of the riders CoM relative to the bike's down tube

We can see the graph roughly mirrors the motion you feel in real life:

1) Riders enter the berm pushing the bike down and extending length
2) Riders maintain pressure throughout the berm and compresses near the end
3) When riders exit the berm they push the bike down again and re-extend.

Body-height window:

$$0.27803\ m \ \leq\ l(t)\ \leq\ 0.59559\ m.$$

Squat/extend acceleration limits:

$$-\ 8.6648\ m/s^2 \ \leq\ \ddot{l}(t)\ \leq\ 30.1478\ m/s^2.$$

The researchers then substituted these bounds into their optimal control problem to determine the optimal pumping technique mathematically.

What the Model Predicts (and how it matches good riding)

The researchers solved the optimal-control problem for a 5-second ride segment that includes the two steep corners and two short straight sections. They started with the rider being in a neutral position, traveling at an angular velocity $\dot{\phi}$ of pi/3 rad per or 9.43 meters per sec, and entering on the beginning section of two opposite corners.

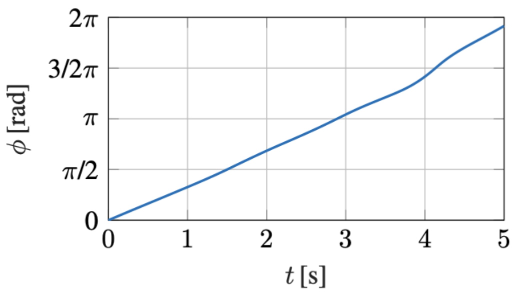
Then, the researchers plugged in the physical parameters into the dynamic constraint(equation of motion):

m^b	m^r	g_{grav}	R	r	λ
15 kg	80 kg	9.8067 m/s	3 m	1 m	3

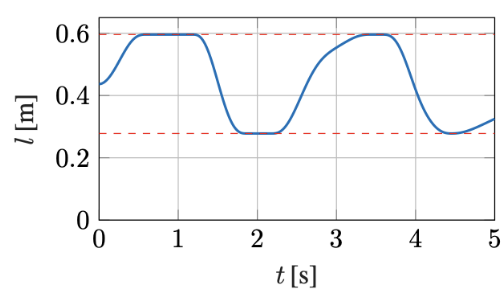
TABLE I: Physical model parameters

The track constants R, r, and lambda determine the sharpness and bankness of the corner, with R=3m, r=1m, and λ =3

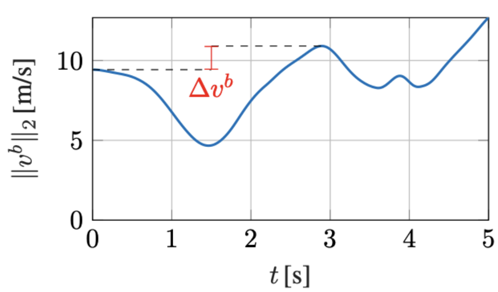
Finally, using MATLAB and IPOT the researchers solved the optimal control problem, successfully simulating a complete cycle through the track. This produced four graphs. Remarkabl from fig 8c we can see the velocity increasing from 9.43 to 10.92 from the first berm, yielding a total increase 1.49m/s only in a single berm.



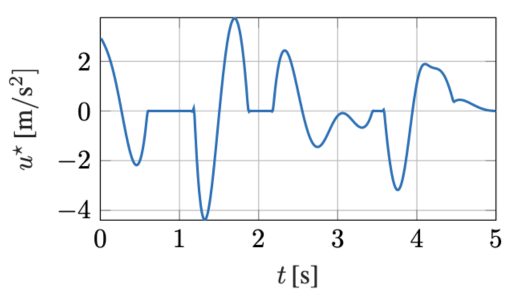
(a) State ϕ over time



(b) State l over time



(c) Absolute bike velocity over time



(d) Optimal input $u^\star$ over time

What the optimal solution does.

- **Kinematics (Fig. 8a):** $\phi(T)$ ends close to 2π—a full pass through the track section with both steep curves.
- **Pose evolution (Fig. 8b):** The optimal profile drives the body **high at entry** (near l_{max}), then **compresses** toward l_{min} across each corner, and **re-extends** later. In other words: **enter tall, compress through the berm, and re-extend** for each berm.
- **Speed gain (Fig. 8c):** Remarkably, between t=0 and t=2.8, which is the first berm, we see **speed increase** of $\Delta v^{b} \approx 1.49\ m/s$, generated **without pedaling**, purely by the reciprocal mass motion (squat/extend).
- **Control signal (Fig. 8d):** The input $u^{*}(t) = \ddot{l}(t)$ shows **short downward-acceleration bursts** (negative then positive spikes) clustered in each corner. Those spikes are the timed “pump” impulses that create extra normal load precisely when the track’s orientation makes a small forward component useful(when entering and exiting a berm, corresponding to our definition of leveraging the change in curvature).

How much faster overall.
They ran a comparison **without pumping** (set $u(t) = 0$, but test several starting heights $l(0)$). The fastest no-input case took **6.13 s** to reach the same terminal angle $\phi(T)$. With the **optimal pumping** $u^{*}(t)$, the time dropped to **5.00 s**. That's a $\Delta t = 1.13$ **(18.43% faster)** for the same path segment.

Bottom line:
Within the paper's simplified two-mass, upright model and experiment-derived bounds, **pumping through a berm** means spending your limited "normal-acceleration budget" **inside the corner** (to harvest speed) and avoiding payback at the exit. The solver's best answer is the pattern good riders already use—**tall in, compress through, extend later**—and the numbers (≈1.5 m/s gain per corner; ≈18% lap-time cut) quantify how much that timing can deliver.

From Model to Trail: a Real-World Translation in Riding Technique

The paper's takeaway is simple: **spend your limited "normal-acceleration budget" inside the corner** and **don't pay it back on exit**. In practice, that means **arrive tall**, **compress through the corner**, and **re-extend later** (ideally once you're back on a straight).

Now, what the model **doesn't** capture (and how real riders adapt):

- **Only normal motion.** The paper restricts the rider to move **orthogonal to the track's surface** (no fore–aft pump). On dirt, riders can **pump slightly forward/back** as well. That can **shift the pattern earlier**, often giving a **high → low → high** *within* a single corner, instead of the model's **high → low (then high on the straight)**.
- **One fixed line.** The solver rides a prescribed line (inner on straights, drifting outward at apex). Outside the lab you can pick lines that change banking and gravity use:
    - **High → low line:** drop from high entry to lower apex/exit to **cash in gravitational energy** while you compress.
    - **Low → high line:** for traction or setup, at the cost of more input work.
- **Two contacts, richer phasing.** With front and rear wheels you get **two timed opportunities** per corner (bar press as the front enters the load ramp, pedal press as the rear reaches it). Skilled riders also **unweight the front** earlier to keep exit smooth.

Beyond Berms: Brief Notes on Rollers and Jumps

• Rollers (pump tracks): You speed up by placing two brief load pulses around each crest—bar press as the front rolls over the crest, pedal press as the rear follows—then staying light on the upslope so you don't give the energy back. The "heaviness" comes from upslope → crest geometry; the backside is where you must go light.

1. **Front wheel at crest (arms compact, legs half-extended).** You're coiling up at the exact moment curvature flips.

2. **Front on downside; rear crosses crest (arm push grows to full extension; legs fully compressed).** Two quick injections: a **bar press** as the front tips over (raising front normal load just as the ground points forward), then a **pedal press** as the rear crests. Each creates a small **forward contact component**

3. **Front in ravine; rear on downside (arms finish extension, legs extend down the back face).** Keep **pedal pressure** while the rear is still on the back face. begin to **unweight the bars** as the front meets the upslope to avoid negative work.
4. **Front on upslope; rear in ravine (legs reach full extension; arms half-compressed; front unweighted).** Now the ground would slow you (upslope). You keep the **front light** and use the **up-kick** to pop your mass upward—maintaining speed while the bike climbs under you.

The two short load pulses—one at the front crest (bars) and one when the rear crests (pedals)—create a small forward push each. Add them up, subtract gravity and drag, and you get your acceleration

• Jumps: Preload on the run-up, then choose: extend on the lip at the point of maximum normal force(Promotion of own research: Normal force is derived through acceleration m* v^2 * k) to trade speed for height (boost) or stay light to preserve forward speed (absorb). The same "press-when-helpful, light-when-hurtful" rule applies, just with a vertical-energy trade at takeoff.

Conclusion

Pumping is a control problem you solve with your body: press exactly while the turn makes you heavy, and rise while it makes you light. The research formalizes this with a minimal two-mass model and an optimizer that times a compress–extend input to harvest the berm's geometry—a clean physics story for the "free speed" riders feel in corners.

Velosolutions Global. (2024, March 6). *2024 qualifier events announced for UCI Pump Track World Championships*. *Pinkbike*. https://www.pinkbike.com/news/2024-qualifier-events-announced-for-uci-pump-track-world-championships.html

Golembiewski, J., Schmidt, M., Terschluse, B., Jaitner, T., Liebig, T., & Faulwasser, T. (2023). *The dynamics of a bicycle on a pump track—First results on modeling and optimal control* (arXiv Preprint No. 2311.07251). arXiv. https://doi.org/10.48550/arXiv.2311.07251