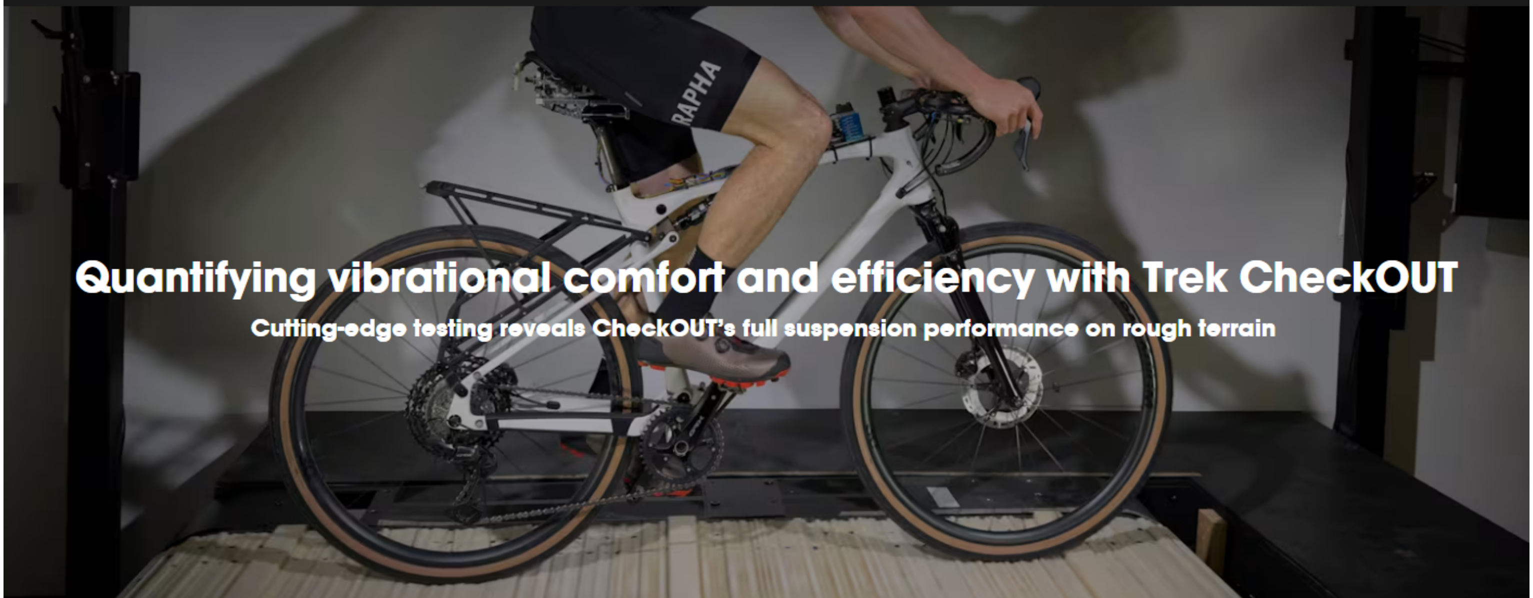

Quantifying vibrational comfort and efficiency with Trek CheckOUT

Cutting-edge testing reveals CheckOUT's full suspension performance on rough terrain

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Today's gravel riding spans everything from smooth dirt roads to washboard descents littered with rocks, singletrack, and beyond. While rigid gravel bikes can handle the tame end of that spectrum, the rapid evolution of gravel riding calls for a bike ready for anything the next adventure might bring.

Shock value

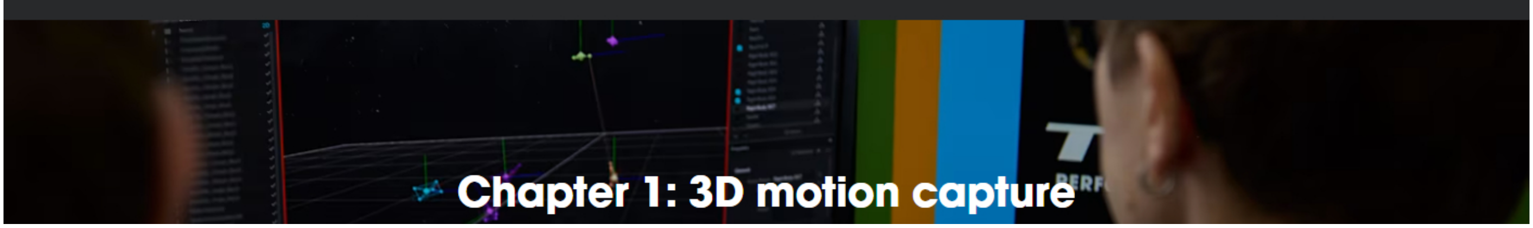
Enter CheckOUT, Trek's rear-suspension equipped gravel rig designed to tame even the harshest, highest-frequency terrain. Years of R&D prototyping have shown that the threshold for full-suspension benefits falls well before the mountain bike trail, and CheckOUT nails that sweet spot. To demonstrate CheckOUT's performance, we ride it alongside a rigid gravel bike on the Trek Performance Research treadmill, using the same rough, controlled surface at five speeds: 6, 9, 12, 15, and 18mph.

We use a Checkpoint SL — a solid choice for everyday gravel riders — to see how the full-suspension CheckOUT compares on bigger adventures and bumpier terrain. To isolate the effects of both full suspension and tire size, we test CheckOUT with two different sets of tires: 55mm and 50mm. The 55mm tires approach CheckOUT's max tire size and demonstrate the bike's full potential with both suspension and extra-large tires factored in. The 50mm tires represent Checkpoint's max tire size, which helps normalize the effects of the tire size in the study and isolate the effects of full suspension.

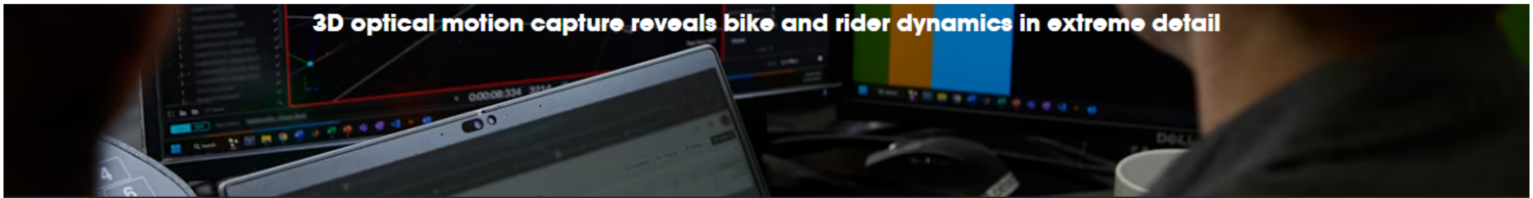
Throughout these runs, we measure both the mechanical and physiological aspects of CheckOUT's performance using three of our lab's key tools: 3D motion capture, on-bike sensors, and a metabolic mask. These tests, tools, protocols, analysis algorithms, and the theories behind them all have been developed over several years of Trek R&D, and the data presented in this paper represent the final stage in a series of tests carried out over the course of CheckOUT's development.

In Chapter 1, 3D motion capture measures a 27–40% reduction in bike and body vibration and a 16–23% reduction in steering variability. In Chapter 2, on-bike sensors reveal a 41.5% reduction in a new vibrational comfort metric. In Chapter 3, the metabolic mask records a 7.3% reduction in rider ventilation, indicating lower fatigue.

As these advanced test methods demonstrate, CheckOUT delivers a major leap forward in gravel control, comfort, and efficiency.



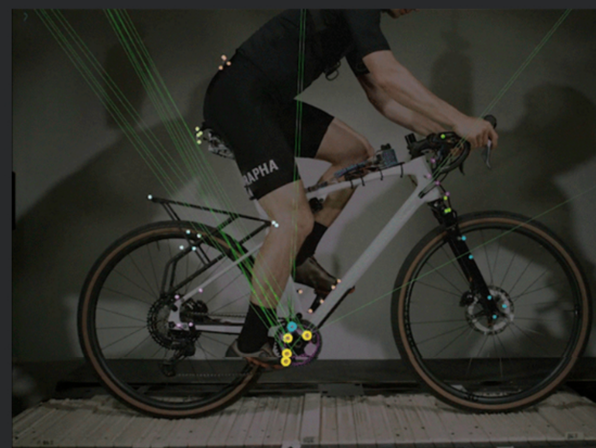
Chapter 1: 3D motion capture



A bike that works for the rider

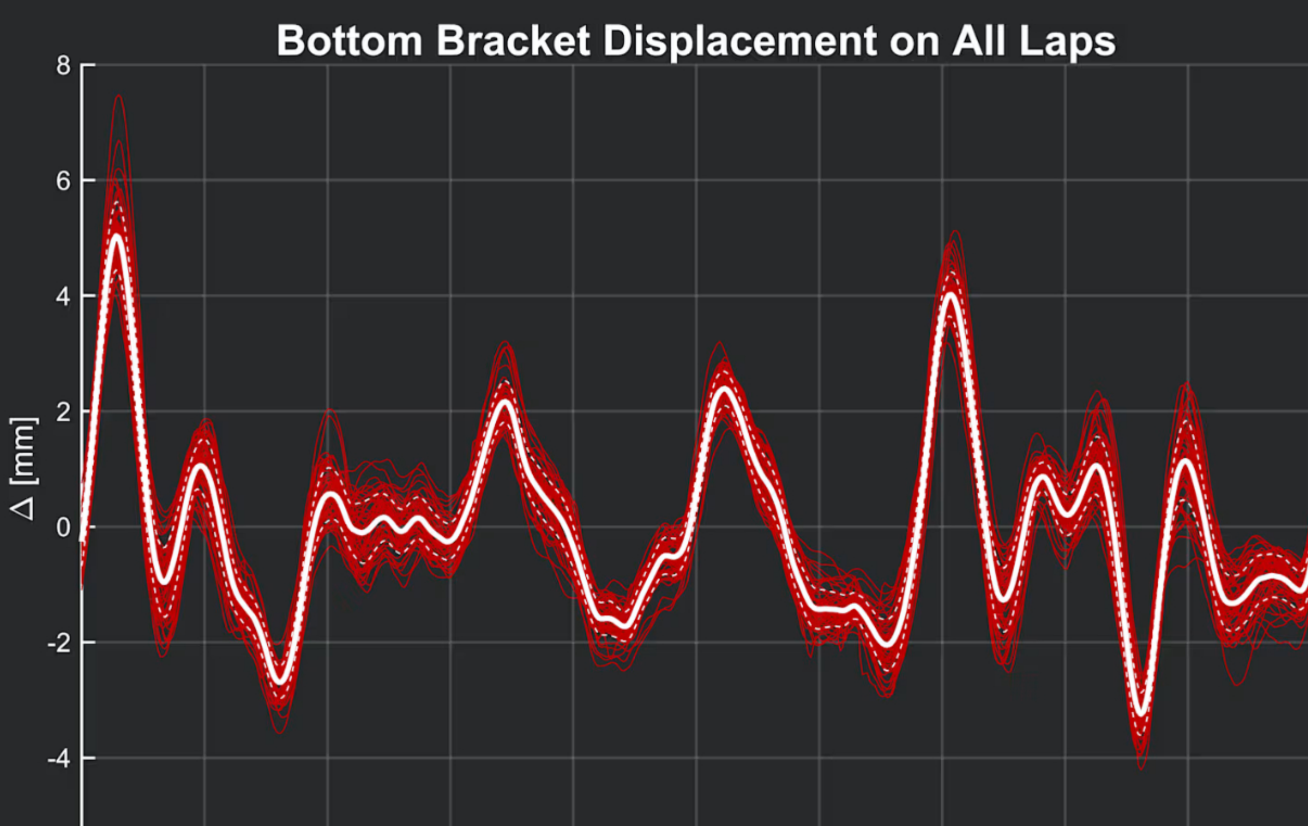
The ways the bike and rider move in response to rough terrain have intuitive ties to both comfort and control. Chassis bounce and bike-rider decoupling usually lead to discomfort and fatigue as the rider naturally puts in extra effort to maintain control and stability. But why do all that work yourself when the bike can do it for you?

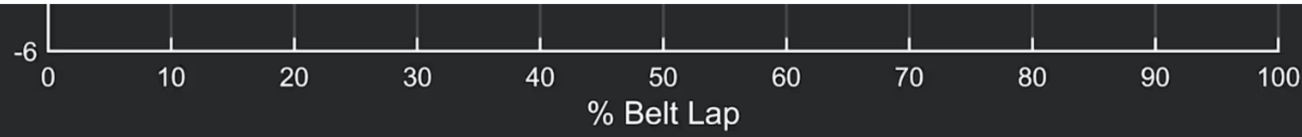
To see what motion the rider contends with, we start with 3D optical motion capture (OptiTrack) to track the bike's main frame at the bottom bracket.



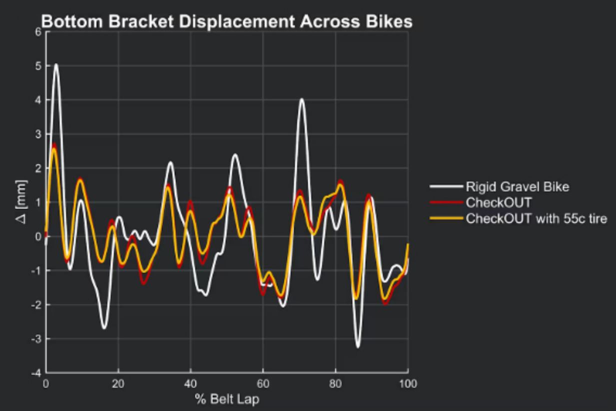
Left: Bottom bracket area markers. Right: Bottom bracket tracking.

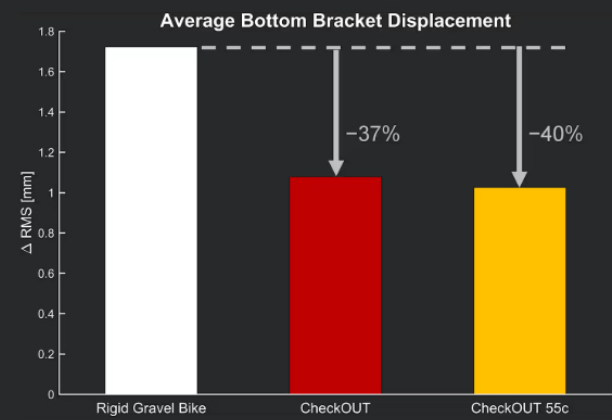
The treadmill gives us repeated "laps" of the riding surface that can be overlaid and averaged to estimate the bike's typical motion and consistency. As an example, the plot below demonstrates this method for the 12 mph rigid gravel bike test condition. The thin red lines represent the up-and-down motion of the bottom bracket on individual laps, while the thick white line shows the average lap, with lighter dashed bars indicating variability (± 1 standard deviation).





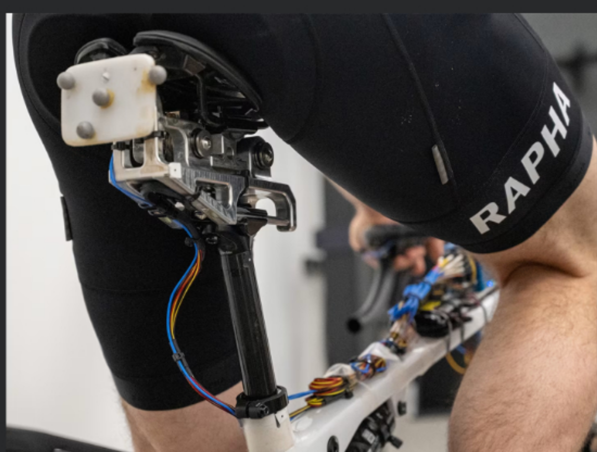
We see that the average lap is a good representation of overall behavior, allowing it to be used to compare bikes. Across all speeds, CheckOUT shows a 37% reduction in vertical motion at the bottom bracket with 50c tires (the same size tires as the rigid bike), and a 40% reduction with 55c tires.



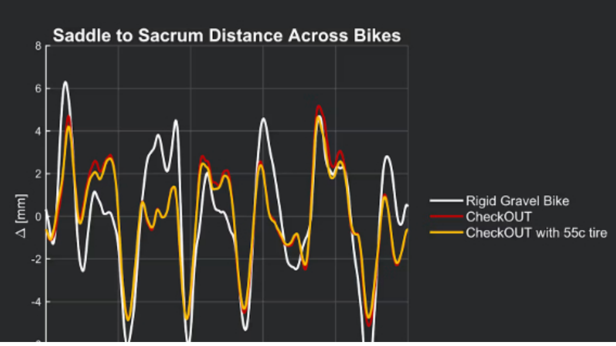


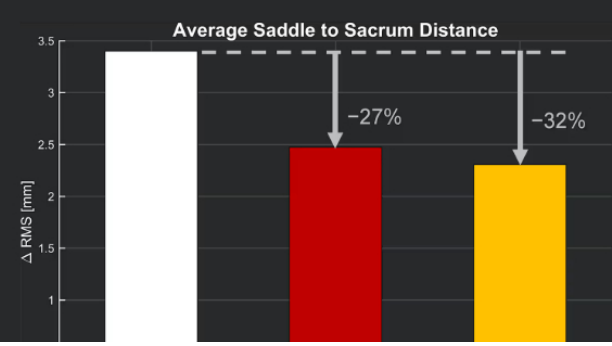
Vertical motion at the bottom bracket. Left: Example raw data for 12 mph. Right: Aggregated data for all speeds. Note: The F/R tire pressures are 19.5/20 psi (55c) and 23.5/24.5 psi (50c), following a popular calculator.

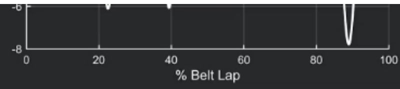
Examining the bike-rider interaction, the benefits of CheckOUT are also clear. Markers on the rider's tailbone area (sacrum) capture basic rider motion, and markers on the saddle track the bike. Comparing these sets of markers allows us to see how well the rider stays coupled to the bike. Typically, a comfortable rider will stay planted on the saddle, and the sacrum and saddle will track together. On harsher terrain, however, the rider can be bounced away from the saddle or choose to just stand slightly, or 'hover' to reduce saddle impacts. Both cases appear as variability in the saddle-to-sacrum distance and indicate an uncomfortable ride that takes extra energy to maintain. Averaged across speeds, CheckOUT boasts a 27% reduction in this variability with 50c tires, and a 32% reduction with 55c tires.

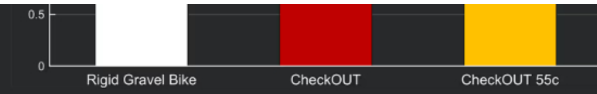


Left: Saddle markers. Right: Saddle and sacrum tracking.



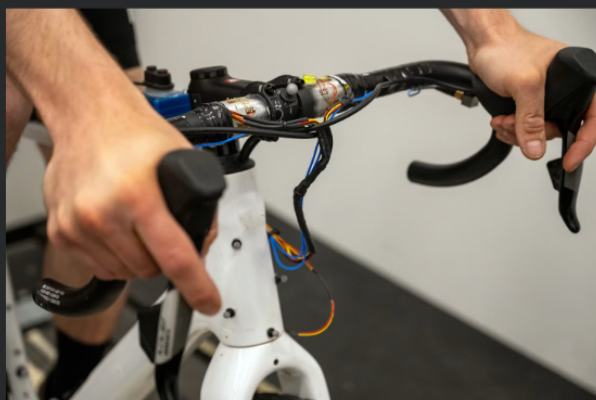


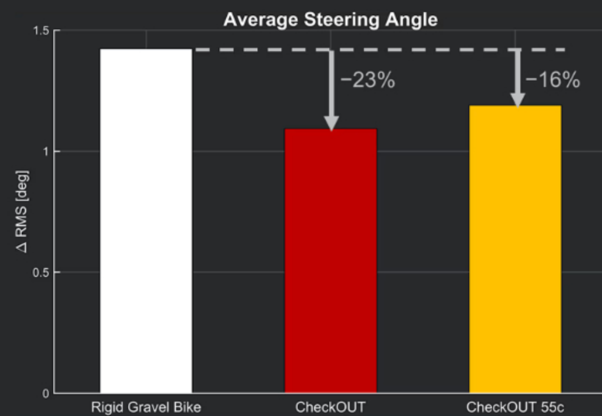




Saddle to sacrum distance. Left: Example raw data for 12 mph. Right: Aggregated data for all speeds.

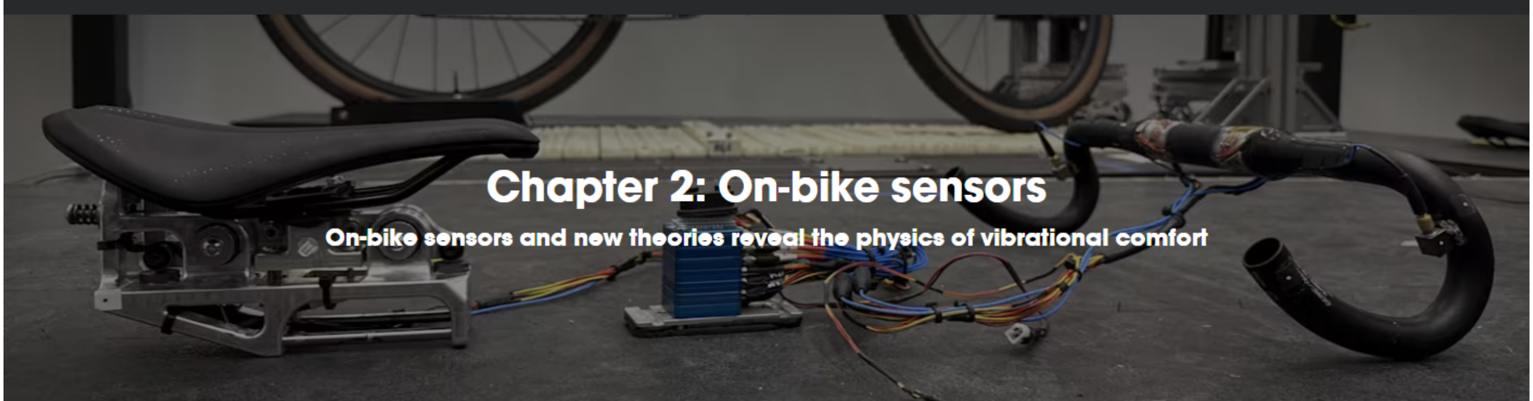
Finally, we assess ride handling by measuring variability in steering angle. Presumably, smaller steering corrections imply that the bike may feel more planted and comfortable to handle. The data suggest an improvement on CheckOUT, with a 23% reduction in steering variability on CheckOUT equipped with 50c tires and a 16% reduction with the 55c tires.





Left: Steering angle markers. Right: Average steering angle variability for all speeds.

Ultimately, 3D motion capture reveals bike–rider system dynamics and makes a compelling case for CheckOUT's suspension benefits, pointing to gains in both comfort and control. In Chapter 2 we dive deeper into the science of quantifying vibrational comfort with on-bike sensors, and in Chapter 3 we link it to rider effort and speed with a metabolic mask.

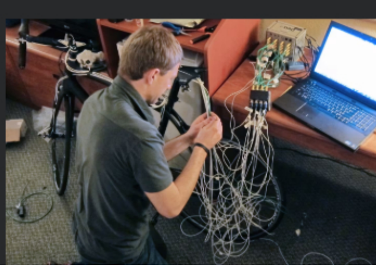


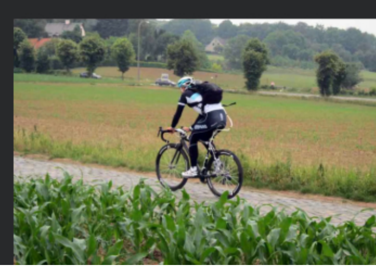
Chapter 2: On-bike sensors

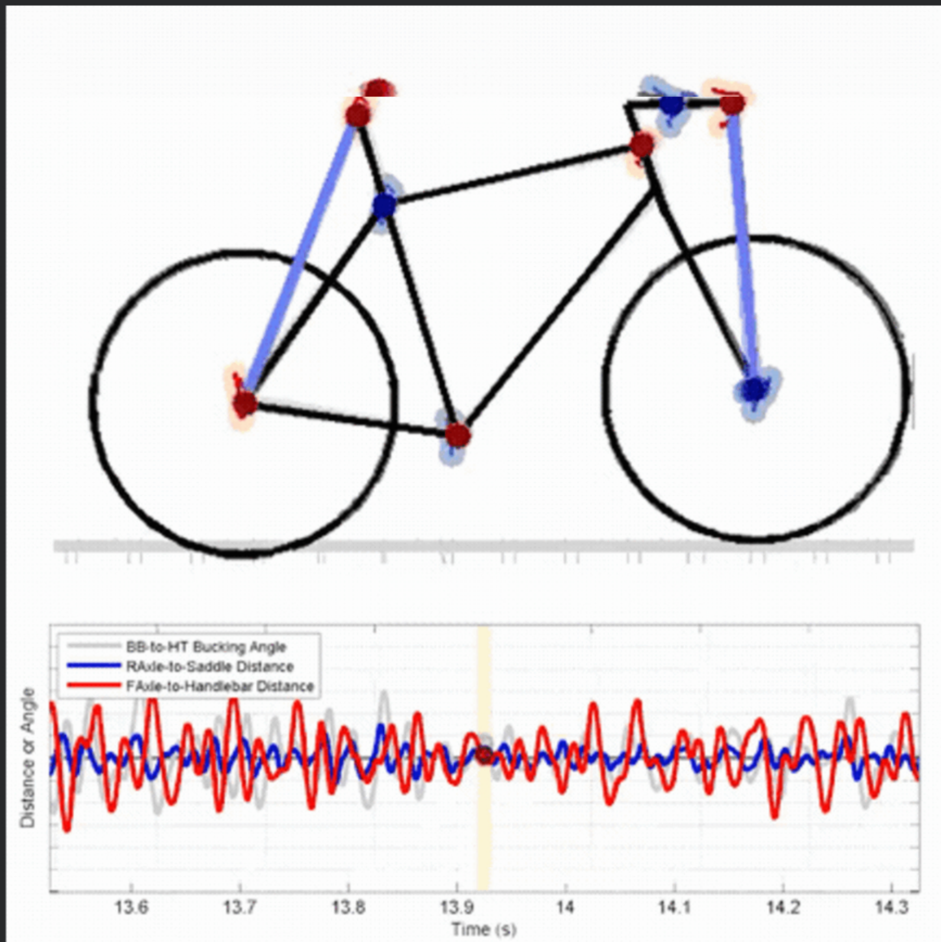
On-bike sensors and new theories reveal the physics of vibrational comfort

Human vibration

Since 2010, Trek engineers have traveled the world testing bicycle vibration using scientific-grade accelerometers and advanced analysis techniques. This testing has unveiled key insights into bicycle dynamics and design.

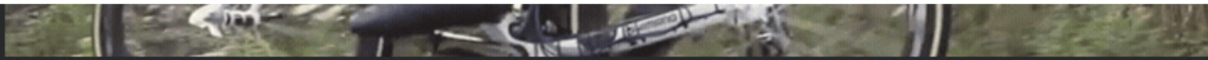






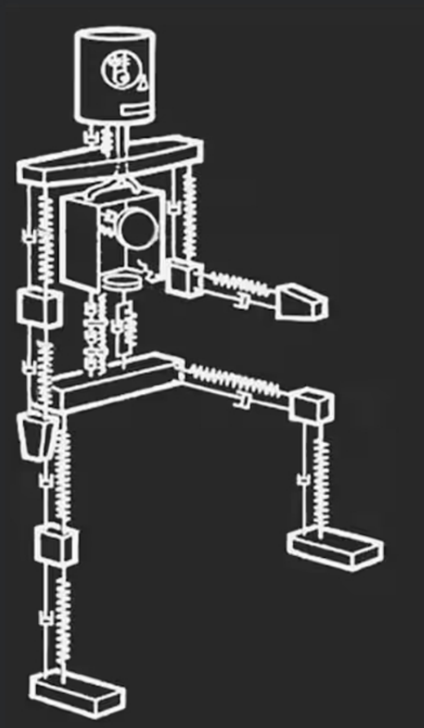
Accelerometer instrumentation, testing, and analysis, circa 2010-2014.

However, we quickly learned that these on-bike accelerometers alone cannot always quantify the rider's perceived comfort. As discussed in Chapter 1, the bike and rider can move very differently, so linking accelerometer data to actual rider comfort is not always straightforward.



Bike-body interaction observed during 2013 Trouée d'Arenberg cobblestone testing.

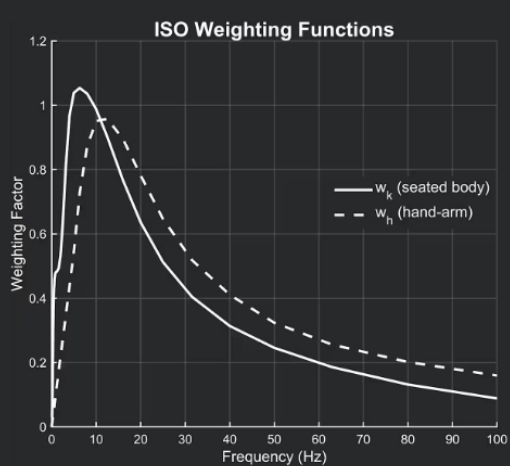
Not only does the rider articulate their joints and hover their body to act as suspension, but the rider's body tissue itself behaves as a complex spring–mass–damper system whose resonances affect how vibration is transferred and absorbed. The result is a constantly changing interplay between bike and body.

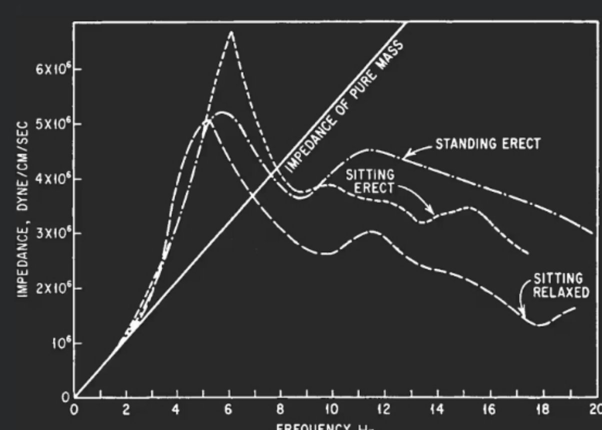


Body component	Resonant Frequency (Hz)
Whole body, sitting vertical	5-6
Abdominal mass	4-8
Abdominal wall	5-8
Abdominal viscera	3-3.5
Hip, sitting	2-8
Main torso	3-5
Shoulder, seated	4
Head, sitting	2-8
Head/shoulder, seated	4 -5
Shoulder/head, transverse rib	2-3
Limb motion	3-4
Spinal column	8
Thorax	3.5
Eyeball	40-90
Eardrum	1000
Hand	1-3
Hand and fingers	30-40
Chest wall	60
Anterior chest	7-11
Foot, seated	>10

Human body resonances [1,2]

To account for human body dynamics, many industries predict comfort using standardized "ISO weighting functions" to rescale accelerometer measurements at human-machine touchpoints. However, we have found that these functions and related metrics, such as Vibration Dose Value [3], often fail to capture the highly dynamic nature of an active cyclist bouncing over rough terrain.





Left: ISO weighting functions for human vibration [3,4]. Right: Human body vibration varies greatly with even static changes in muscle activation [5].

Contact force

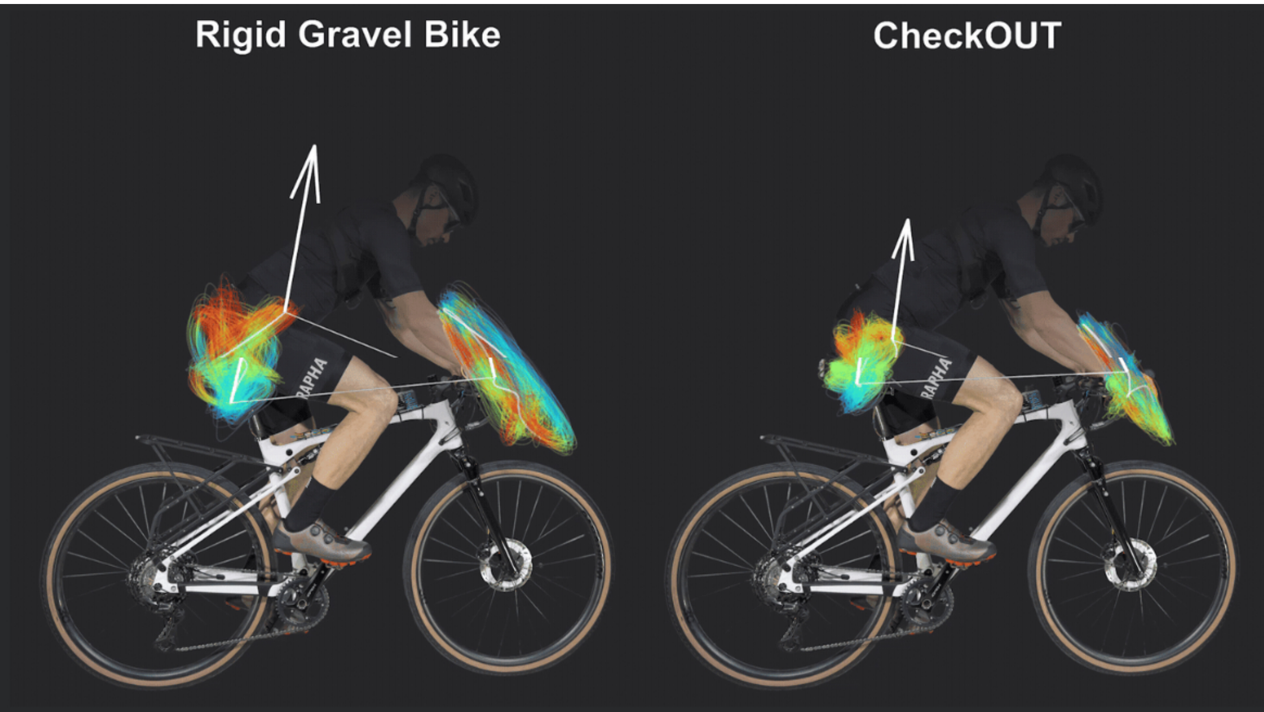
Vibrational comfort depends not just on the bike's vibration but also on the level of physical connection to the rider. For example, when hitting a bump, a cyclist intuitively reduces this connection by relaxing their elbows or lifting up off the saddle. We can quantify this connection by measuring the contact force between the bike and rider at the touchpoints.

Measuring this force is much harder than measuring acceleration, and we have iterated through many designs of strain-gauged and integrated load cell stems, seatposts, saddles, and handlebars.

Various force-sensing components from throughout the years of R&D testing.

In their current version, our custom instrumented saddle clamp and handlebar measure the forces (and accelerations) in the vertical and horizontal directions at the saddle, left hand, and right hand – all at 5,000+ samples per second.

Measuring force together with motion allows us to visualize the full physics of rider-bike interaction and begin to get a sense of CheckOUT's comfort gains.



Force magnitudes (colorized) and vectors (10× slow) over magnified displacement point clouds at 12 mph.

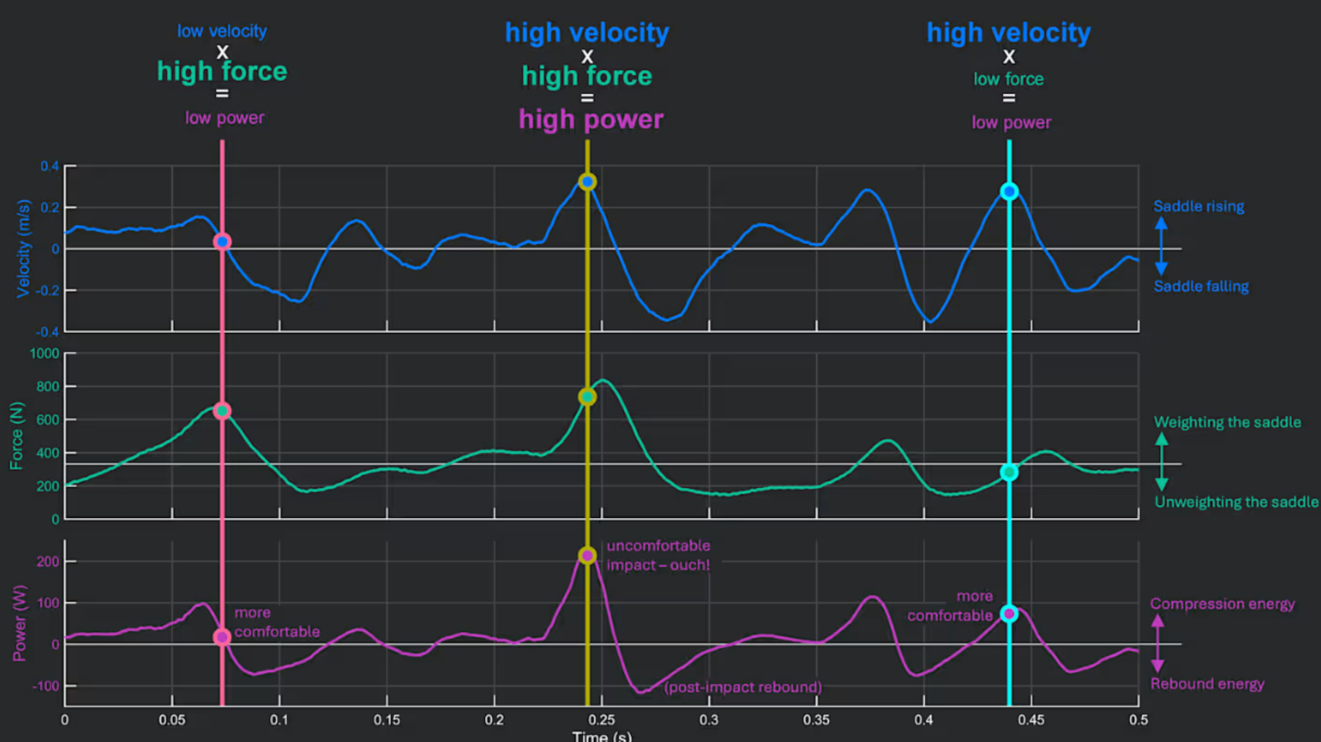
Vibrational energy and rider comfort

Here's where all the pieces come together! Research shows that vibrational comfort best correlates to not force or motion alone – but to vibrational power [7-9]. Not coincidentally, we can calculate power P by simply multiplying force F by velocity v (from the accelerometer):

$$P(t)=F(t)\cdot v(t)$$

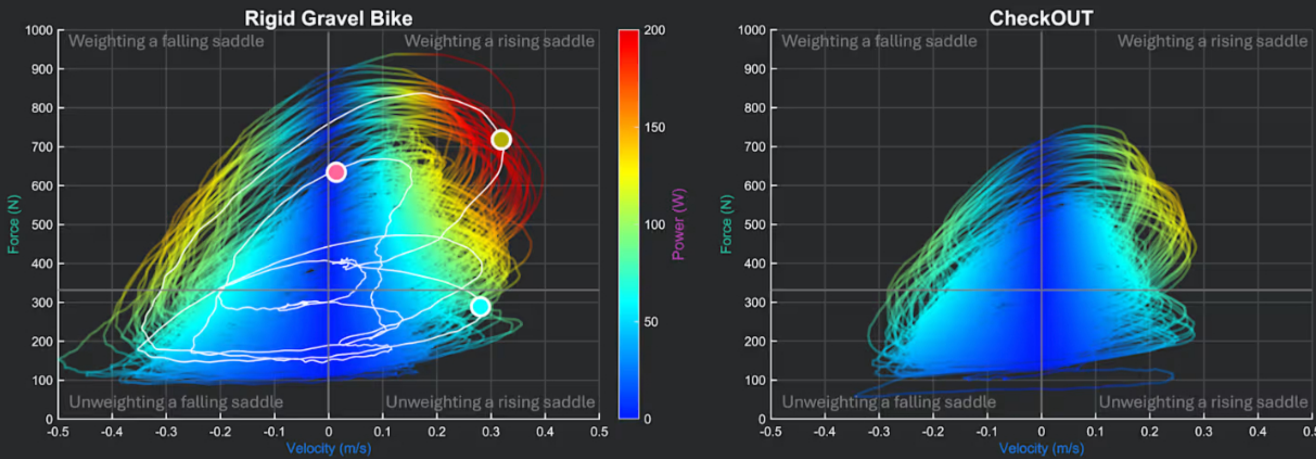
This equation is deceptively simple yet, well, powerful! At each instant, $v(t)$ answers "is the bike moving quickly?" and $F(t)$ indicates "is the bike also in solid contact with the rider?" The resulting instantaneous power $P(t)$ weights the importance of each individual bump by how much the rider actually feels it. Unlike the standard ISO weighting functions, this metric adapts in real time to the ever-changing dynamics of cycling over rough terrain.

For example, in this snippet of raw data at the vertical saddle location, a wide range of force-velocity interactions play out, all in just 0.5 seconds.



Snippet of time history data for the rigid bike saddle (vertical axis) at 12 mph.

Zooming out from the 0.5-second snippet, we can visualize the full 40-second trial of force-velocity-power data in a colorized cross-plot. In the left plot below, we see the same rigid gravel bike run as above, with the same three moments in time marked as dots along the trace. On the right is the comparable condition for CheckOUT. The rigid gravel bike shows a wide spread, especially in the upper right quadrant where force and velocity spike together to create the hardest-felt upward impacts, while CheckOUT's plot is more compact, with far fewer points in the high-power zones.

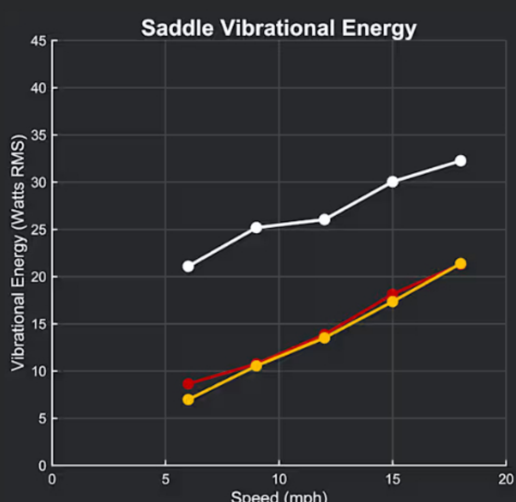


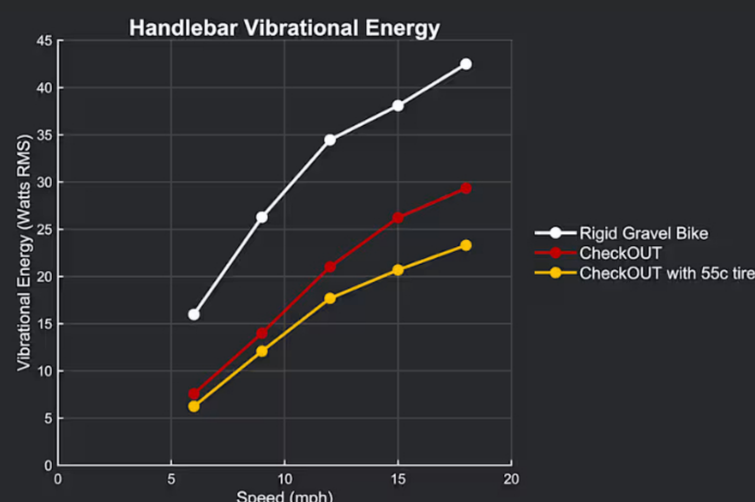
Force-velocity cross-plot for the rigid bike saddle (vertical axis) at 12 mph.

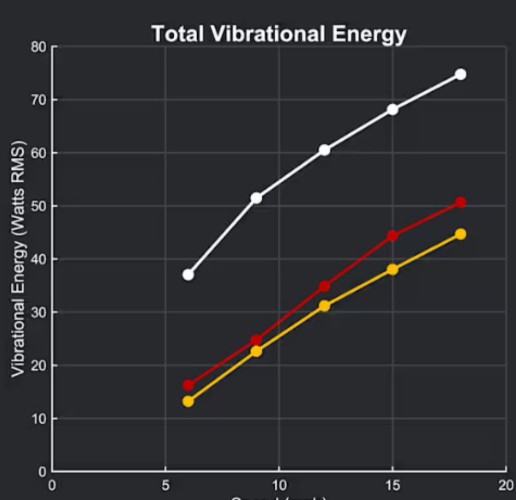
While those point clouds are fascinating, showing every condition would require 90 such plots (3 bike configurations × 5 speeds × 3 touchpoints × 2 directions). To make comparisons practical, the final step is to aggregate the instantaneous power into a single vibrational comfort metric for each run.

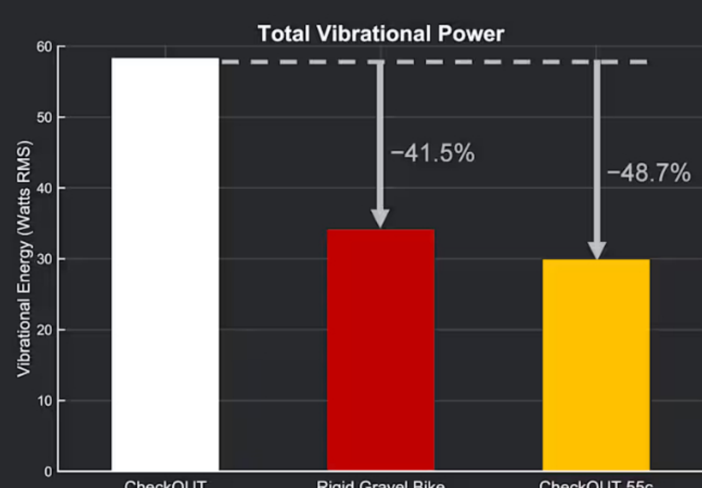
In their seminal 1966 study on vibrational power, US Army researchers first proposed a simple "average absorbed power" calculation [7]. More recently in 2022, researchers at the University of Sherbrooke compared a wide set of vibration, force, power, and energy metrics and found that RMS power and energy correlate best with dynamic comfort, outperforming accelerometer-only and force-only metrics even when ISO weighting is applied [8].

Following this most recent research, we report RMS vibrational power at the saddle and handlebar in the plots below. To avoid confusion with pedaling power, we refer to both vibrational power (W) and energy (J) collectively as Vibrational Energy.









"Vibrational Energy" (RMS power) summed across all touchpoints and directions.

In these plots, we see that CheckOUT's vibration benefit is consistent at both the saddle and handlebar across the full range of test speeds, with a

41.5% overall reduction in Vibrational Energy.

Additionally, we see that the benefit from CheckOUT's suspension far exceeds that from the larger 55c tire alone.

To be thorough, we validate our main result against several alternative metrics and approaches, summarized in the table below. Static-force subtraction isolates the forces due to impacts [8], and a zero-phase high-pass filter prevents artificial drift when integrating acceleration to velocity. We typically use a 5 Hz cutoff to remove pedaling content (~2–3 Hz, 60–90 rpm), but we also report a 1 Hz variant to include pedaling effects. Across all processing variations, CheckOUT's reduction remains in the 37–42% range.

CheckOUT % Reduction	Metric Description	Metric definition (reference)	Static Force Subtracted Out?	High-pass Filter For Velocity
41%	RMS Power (W)	Drouet et al. (2022)	Yes, 2 s moving avg	5 Hz
42%	Energy (J)	Drouet et al. (2022)	Yes, 2 s moving avg	5 Hz
42%	Mean Absorbed Power (W)	Pradko & Lee (1966)	No	5 Hz
37%	RMS Power (W, including cadence freq)	Drouet et al. (2022)	Yes, 2 s moving avg	1 Hz

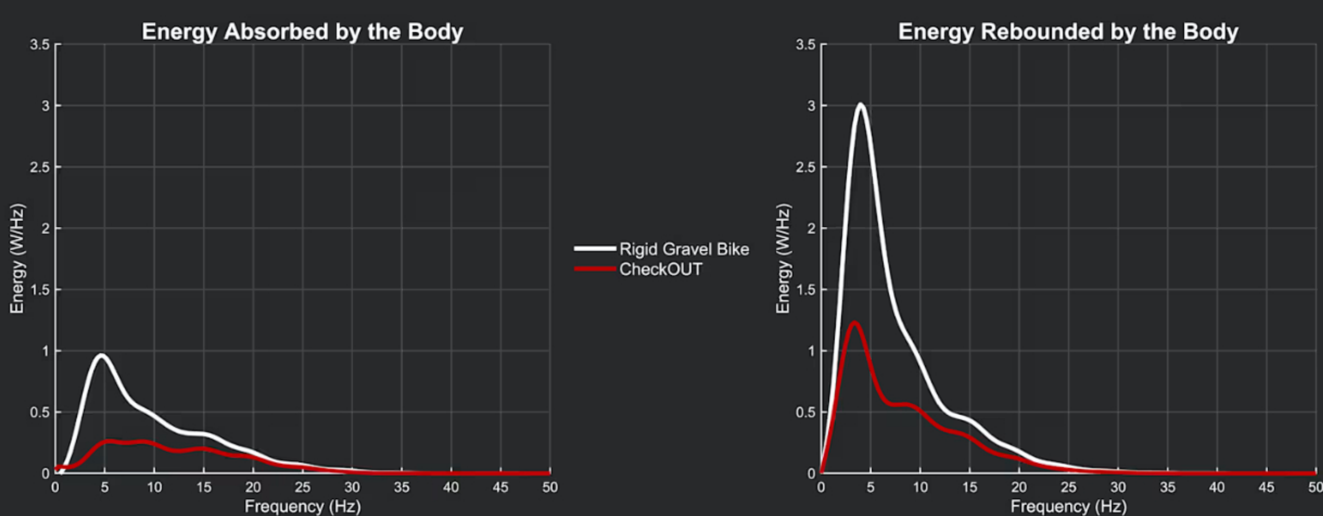
Validation across several versions of power and energy metrics.

Frequency analysis

Finally, we calculate the force-velocity cross-power spectral density (CPSD), an advanced method to reveal the deeper physics of Vibrational Energy flow into the body [10-13] (to our knowledge, a first in cycling science).

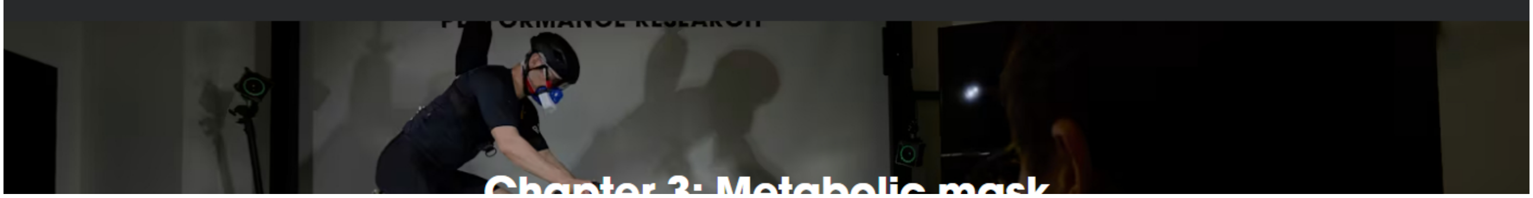
This CPSD maps out how the energy that enters the rider's body is distributed across the frequency spectrum. And by comparing the phase between force and velocity, it separates the energy that the body absorbs (like a damper) from the energy that the body rebounds back to the bike (like a spring) [10, 11, 14]. It is believed that the absorbed energy is linked to energy loss, fatigue, and tissue strain, whereas the reflected energy is linked to bounciness and discomfort [10, 15, 13].

Below, we see the absorbed and rebounded energy spectra for vertical vibration at the saddle. In these plots, we see not only a drastic reduction in energy for CheckOUT but also a unique insight into how the body responds to bicycle vibration. Unsurprisingly, most of the energy content aligns with the natural frequencies of the seated human body [1-5].



Force-velocity CPSD at the saddle (vertical axis), averaged across all speeds. Left: absorbed power spectrum $\Re\{SFv(f)\}$. Right: reactive power spectrum $\Im\{SFv(f)\}$.

We can further use CPSD's phase and coherence outputs to dig even deeper into bike-rider connection, but we leave this section as a glimpse of Trek Performance Research's mission to push the frontiers of cycling science and uncover the unique insights that drive innovations like CheckOUT.



Chapter 3: Metabolic mask

The metabolic mask reveals how comfort translates to speed

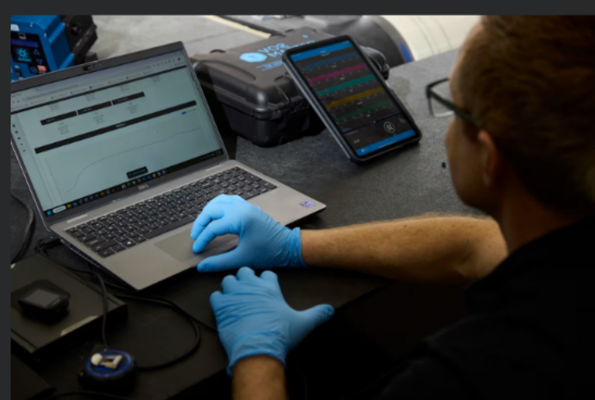
While we have shown that CheckOUT delivers a smoother, more comfortable ride, does the old adage "smoother is faster" hold true? To ask this question in technical terms, does the reduced Vibrational Energy transmitted to the body result in a longer time to exhaustion? To find out, we measure the rider's metabolic cost of pedaling and controlling the bike, i.e. energy expenditure, using a VO2 Master portable metabolic mask.

In this dedicated set of test runs, our test rider pedals on rough terrain for five minutes per trial on CheckOUT and a rigid gravel bike. Each condition is repeated, and the entire test is repeated on a different day to ensure replicable results.

Every efficiency study in the Trek Performance Research lab uses the VO2 Master portable metabolic mask. Its portability enables both road and trail outdoor testing, as well as safe, untethered treadmill testing on rough terrain in the lab. We turn to metabolic testing for a simple reason: power meters only tell part of the story.

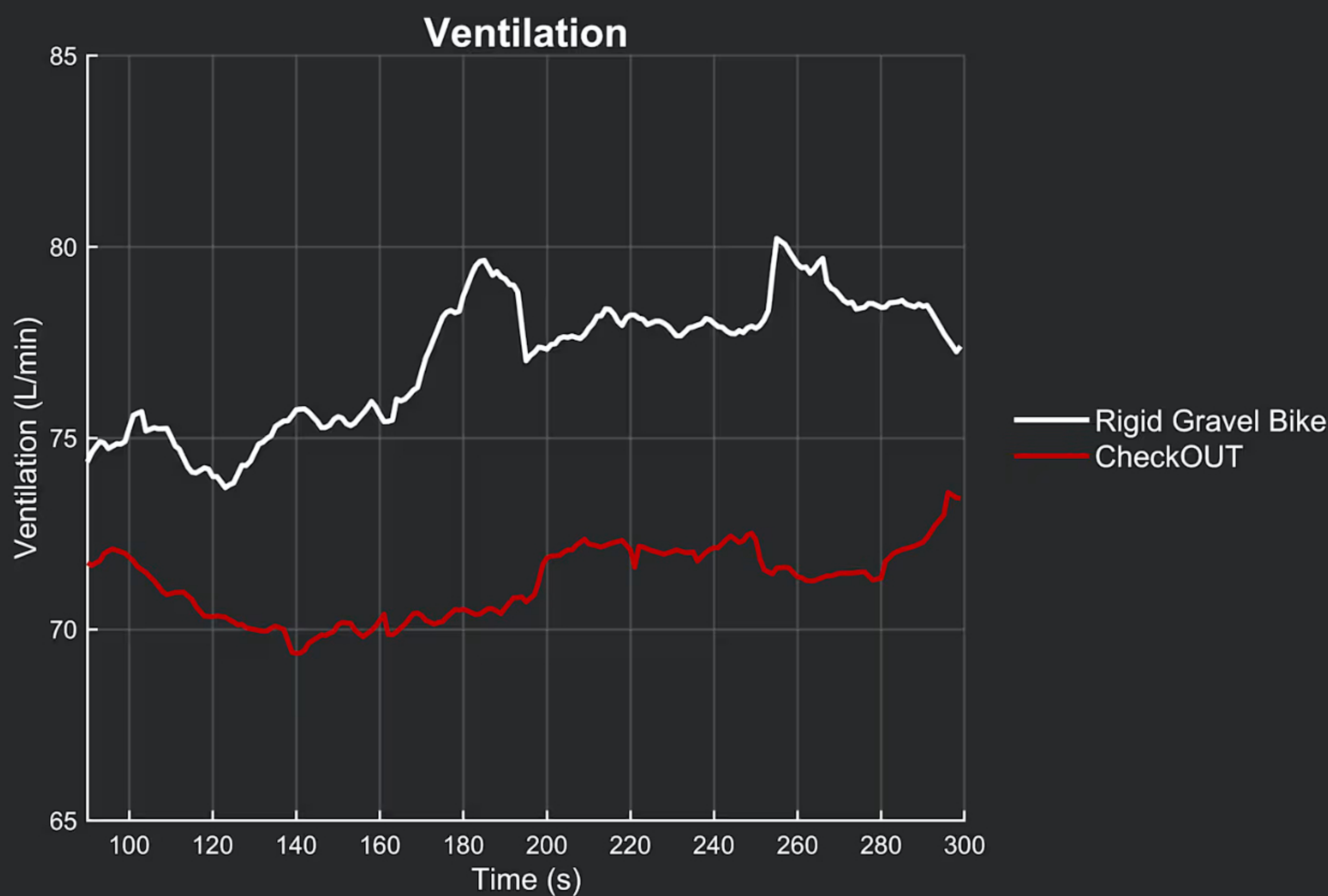
This is especially true on rough terrain where a rider naturally smooths the ride by articulating and hovering their body above the bike to compensate for insufficient suspension. This ride-smoothing comes at a high metabolic cost, or high energy expenditure, that does not contribute towards rotating the crank. This means the power meter completely misses this effort. A power meter also has no visibility into the metabolic cost of the rider's body absorbing Vibrational Energy as described earlier.

During our test, the test rider reported a "burning" sensation in their arms after the rigid gravel bike runs. This sensation of muscle burn occurs when utilizing glycolysis, i.e. metabolizing glucose. This process builds up pyruvate in the working muscles. Pyruvate is then converted to lactate, a very useful fuel for the working muscles, which yields hydrogen ions. Accumulation of these hydrogen ions in the muscle cells decreases the pH of the muscle, which is felt as a "burning sensation." While we do not have a muscle-burn-o-meter, we can directly measure another change that happens as the rider utilizes glycolytic metabolism: increased ventilation.

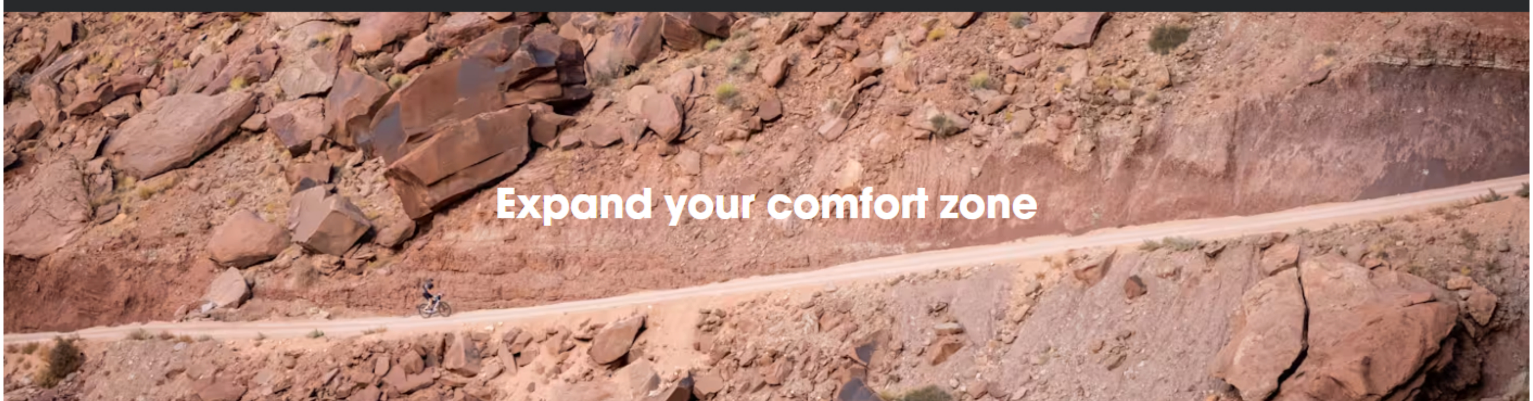


Left: Mask calibration. Right: Data Monitoring

Glycolysis leads to an increase in the carbon dioxide level in the blood, prompting the body to increase ventilation to expel it. Ventilation [L air/min] is the product of the air volume exchanged per breath [L/breath] and the breath rate [breaths/min]. The VO2 Master mask uses an airflow sensor to measure ventilation. The plot below compares ventilation between CheckOUT and the rigid gravel bike, using data from the final 3.5 minutes after a 1.5-minute settling-in period.



As seen in the plot, the rider shows a **7.3% reduction in ventilation** on CheckOUT versus the rigid gravel bike on this rough terrain. Translation: When the terrain gets this rough, CheckOUT provides a longer time to exhaustion!



Over the past decade-plus, Trek Performance Research has built an innovative toolbox of instruments, methods, and theories to dig deep into cycling physics and turn those insights into better bikes for better rides. In this study, those tools all agree: CheckOUT sets a new standard for gravel control, comfort, and efficiency – ready to take on whatever adventure you can dream up!

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