Comparison of VO2 and Body Kinematics for Three Cycling Modes

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by

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**Introduction**

Cycling research in a laboratory has an advantage of being more tightly controlled compared to field studies; however, consideration must be given to ecological validity for the results to be best applied to its target population and environment. This was clearly demonstrated by Jones and Doust (8) where they reported treadmill running to be metabolically lower ($p < 0.05$) then outdoor running at the same velocity and incline. Cycling research is often targeted towards high-level cyclists interested in understanding cycling physiology and improving performance. Therefore, research results are most applicable when utilizing methods that best mimic conditions of the target population while still maintaining the control advantages that the laboratory offers (4, 9, 13).

In cycling, it is quite common for researchers to utilize a stationary trainer, rollers with the handlebars fixed in place (F rollers), or a cycle ergometer to simulate road cycling for the purpose of measuring metabolic economy, power output, and muscle activation. Gnehm et al. (5) measured metabolic economy by measuring oxygen consumption (VO$_2$) of elite cyclists in different racing positions on F rollers allowing the rider to forgo balance. F rollers were chosen because the cyclists stated that the rollers resemble road conditions best. They reported a greater metabolic cost at sub-maximal intensity in the aero bar posture compared to the upright posture with an aero posture VO$_2$ of $48.8 \pm 1.3$ mL·kg$^{-1}$·min$^{-1}$ and an upright posture VO$_2$ of $47.3 \pm 1.2$ mL·kg$^{-1}$·min$^{-1}$ ($p = 0.002$) (5). In contrast, several other studies reported no statistical difference for VO$_2$ between the upright, drops, and aero positions (2, 6, 12). Prior to the Gnehm et al. study, Origenes et al. (12) measured VO$_2$ on a cycle ergometer in the upright and aero posture. They reported no statistical difference ($p > 0.05$) in VO$_2$ for maximal bouts. Maximal data were reported as follows, $54.3 \pm 6.3$ mL·kg$^{-1}$·min$^{-1}$ and $53.4 \pm 6.9$ mL·kg$^{-1}$·min$^{-1}$ for the upright and
aero positions, respectively. Dorel et al and Grappe et al. (5, 6) performed a similar study to
Gnehm et al. using a cycle ergometer and reported no statistical ($P > 0.05$) difference in VO$_2$ for
the three postures tested. The discrepancy between these results may be due to the different
cycling modes used, namely F rollers versus a cycle ergometer, particularly because the F rollers
allowed the participants to use their own bicycles. This logically leads investigators to question
if using F rollers, stationary cycling trainers, or cycle ergometers are best for measuring
metabolic economy variables or if there are alternate methods that better simulate road cycling
conditions as suggested in the cycling review by Hug and Dorel in 2009 (7).

While F rollers, trainers, and cycle ergometers can offer ease of use and accurate power
measurements, they lack one important component that road cycling requires, namely balance.
Rider balance should be incorporated to better mimic racing conditions where the rider is
constantly using minor muscle movements for course correction, balance adjustment, and
stabilization. This concept has been investigated in weight lifting exercise, where researchers
have noted an increase in EMG activity for free weights relative to machine weights, citing a
higher activity in the stabilizer muscles used to support the primary movers for free weights (10,
15). Having the bike held stationary may also slightly alter the riders natural movements,
particularly as they reach higher power outputs or during acceleration. This is because as the
cyclist requires a speed and/or power increase, body movements may become less rigid and then
must react against the rigidity of the stationary bicycle or cycle ergometer. In addition, cycling
on road conditions allows for lateral and angular movement (7) that can result from the cyclist’s
form becoming less rigid due to a power and speed increase and controlling or allowing for that
movement may have an effect on the cyclist’s metabolic economy and ability for power output.
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To address these concerns, cycling rollers with the bicycle unfixed (UF rollers) may be useful as an effective means for studying metabolic economy, via introducing rider balance and; therefore, more closely mimicking road cycling conditions. UF rollers introduce a more realistic mental aspect to the testing as well, because they require the rider to focus on holding a steady line, whereas a trainer or a cycle ergometer allows the rider to focus solely on power output without as much concern for technique. In addition to the UF rollers, a power meter can be implemented directly on the bicycle to allow for accurate power measurements and some rollers offer a variety of resistances, when in conjunction with varying gear ratios, give rollers the versatility needed for achieving the different resistance levels offered by a stationary trainer or cycle ergometer. Examining body and bicycle movements are important in understanding the kinematics of cycling. A motion analysis system can be used to both, record the body and bicycles lateral and angular movements, as well the bicycle’s directional movements. Differences found in the kinematics could offer an explanation to differences that may occur in metabolic economy relative to each cycling mode.

A comparison of these different methods for studying cycling is a logical pursuit to investigate any differences in metabolic and biomechanical variables. If differences are not found, this study will offer more validation to the results of past studies that have used a cycle ergometer, F rollers or a stationary cycling trainer. If differences are found, then this study could be considered as a basis for altering methods for cycling data collection in the future. Therefore, the purpose of this study was to examine metabolic economy in well-trained cyclists during three different cycling modes: (a) UF rollers, (b) cycling trainer, and (c) cycle ergometer. It was hypothesized that VO$_2$ and kinematics would differ between the modes, with the UF rollers yielding a greater metabolic cost than the other modes at the same power. By utilizing a motion
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analysis system, we sought to quantify key body and bicycle movements such as, bicycle lean, yaw, and steering, for the purpose of offering a logical explanation that may factor into the mechanism behind any metabolic changes between the modes.

**Methods**

This study was approved by the Utah State University institutional review board and all participants signed a written consent form prior to participating in the study.

Participants: Seven highly-trained, male cyclists that were proficient on rollers were selected to participate in this study; they were recruited from local cycling teams and clubs. Each participant had a minimum of 5 years cycling experience and often competed in events.

**Table 1.** Physiological and anthropometrical characteristics of participants, and testing conditions.

<table>
<thead>
<tr>
<th>n = 7</th>
<th>mean ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>30 ± 9.8</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>180.86 ± 7.78</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>74.56 ± 11.65</td>
</tr>
<tr>
<td>VO$_2$ Max (ml·kg$^{-1}$·min$^{-1}$)</td>
<td>65.3 ± 4.8</td>
</tr>
<tr>
<td>VO$_2$ Max (L·min$^{-1}$)</td>
<td>4.9 ± 0.8</td>
</tr>
<tr>
<td>Testing Temperature (C)</td>
<td>19 ± 1.3</td>
</tr>
<tr>
<td>Altitude (M)</td>
<td>1382 ± 0</td>
</tr>
</tbody>
</table>

Protocol: All participants performed a warm-up session for a self-selected length immediately prior to testing. Following the warm-up, each participant underwent a graded exercise VO$_2$ peak test (increase of 50 Watts per min) in the upright position, remaining in the saddle while riding his own bicycle on a CycleOps$^{\text{im}}$ Super Magneto Pro trainer. All VO$_2$ testing was done using a Parvo Medics TrueMax 2400 Metabolic Measurement System that was calibrated for volume and percent concentration of O$_2$ and CO$_2$. Prior to the VO$_2$ peak test, participants were instructed to increase power on their own if they felt they could not make it to the next stage (1 min). The trainer mode was selected for a VO$_2$ peak test because it was a good compromise between rollers and an ergometer, allowing for the participants to use their own bicycles while disregarding balance. VO$_2$ peak was identified when the rider reached a
minimum respiratory exchange ratio (RER) of 1.10. A heart rate that was close to the participants predicted max (220 – age) was also used to further verify VO₂ peak. Power output was measured during the VO₂ peak test via a Power Tap SL⁺™ hub. The same power tap setup was used with all participants for the VO₂ peak tests as well as the subsequent sub-max comparison tests, except the cycle ergometer mode. Based on the results of the VO₂ peak test, power that corresponded to 75% of peak VO₂ was used for the sub-max comparisons; this power was selected as a high-performance intensity that remained below the participant’s predicted anaerobic threshold. Recovery time from the VO₂ peak was self selected by the participant with an understanding of the performance requirements that remained in the testing session. A minimum recovery time of 30 min was selected before the sub max bouts began.

Following recovery, each participant began the cycling mode comparison tests on all three modes (road bicycle modified Monark ergometer, CycleOps™ Supermagneto trainer, CycleOps™ aluminum rollers with magnetic resistance) in randomized order. All participants were given their target power that corresponded to 75% of VO₂ max and were asked to maintain that power across all 3 modes being tested and to remain in the saddle throughout. For the UF rollers and trainer modes, participants were asked to seek a gear that equaled their target power at 90 revolutions per minute (rpm), if necessary they could adjust rpm to achieve and hold their target power. Power was measured in Watts via a Power Tap SL⁺™ hub in conjunction with a Jewel Pro™ fixed to the handlebar that gave real-time data of power output. Resistance was set on the cycle ergometer via adjusting weight resistance to give the appropriate resistance at 90 rpm, the cyclist maintained cadence via a metronome. Each bout lasted 4 min to obtain steady state VO₂ on each cycling mode. The last 2 min of each bout was averaged for VO₂, and that value was the source for comparison between modes. Because power could not be exactly
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Matched across the 3 modes, a regression line based on the VO₂ peak test was used to adjust VO₂ values to corresponding values at a constant mechanical power. This was done by the equation:

\[ \text{VO}_2(\text{measured}) - (\text{power}_{\text{mode}} - \text{power}_{\text{trainer}}) / \text{slope}_{\text{regression}}. \]

Motion analysis: Participants and their bicycles were fitted with reflective markers for the purpose of kinematic analysis. A Vicon camera system with T20 model cameras sampled the movements at a frequency of 100 Hz for 1 min during each mode, Nexus software was used to collect kinematic data and convert two-dimensional to three-dimensional coordinates. Thirteen markers total were placed on the participant, eight markers were placed on the bicycle, and the same amount of markers were placed on the cycle ergometer in locations that best matched the locations on the racing bicycles used (Figure 1). All angular movements were measured in degrees, while the absolute position of the rider and the bicycle were measured in centimeters. All of these markers in combination allowed us to analyze bicycle’s absolute position and angular movements, as well as the rider’s overall movements (Figure 1).

Statistical analysis: Statistical package SPSS version 19 was used to run an ANOVA with repeated-measures, within factors, in order to compare VO₂ differences across the 3 devices, with an alpha level set to 0.05.

![Figure 1](image.png)

**Figure 1** A) Reflective markers on the body. B) Reflective markers on the bicycle. C) Kinematic movements.
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Results

Metabolic economy and power variables: After adjusting VO\textsubscript{2} for constant mechanical power, the repeated-measures ANOVA, within factors, reported a significant difference for VO\textsubscript{2} between means of the three modes tested (\(p = 0.015\)). Post-hoc analysis showed the UF rollers to be significantly different than both the trainer and the ergometer with \(p = 0.021\) and \(p = 0.027\) for the trainer and ergometer comparisons, respectively. In contrast, the trainer and the ergometer were determined to have no significant difference (\(p = 0.852\)). A 1.2 ml\cdot kg\textsuperscript{-1}\cdot min\textsuperscript{-1} increase in VO\textsubscript{2} was required for the UF rollers versus both the stationary trainer and the ergometer. This equated to a 2.5% increase in VO\textsubscript{2} for the UF rollers that was required for the rider to maintain the same mechanical power output on the other modes (Table 2), with an effect size of 0.501 partial \(\eta^2\). The mean slope for all participants based on the regression generated from the VO\textsubscript{2} peak test was 7.6692\texttimes, this was used to find the mean Watt difference required for UF rollers if VO\textsubscript{2} was constant, which was 9.3 Watts.

| Table 2. VO\textsubscript{2} and power variables for participants at approximately 75\% of VO\textsubscript{2} max (mean ± SD) |
|------------------|------------------|------------------|
| **UF Rollers** | **Trainer** | **Ergometer** |
| Measured VO\textsubscript{2} (ml\cdot kg\textsuperscript{-1}\cdot min\textsuperscript{-1}) | 48.6 ± 5.0 | 48.0 ± 5.2 | 49.0 ± 4.3 |
| Adjusted VO\textsubscript{2} (ml\cdot kg\textsuperscript{-1}\cdot min\textsuperscript{-1}) | 49.2 ± 5.2* | 48.0 ± 5.2 | 48.0 ± 4.8 |
| Power (W) | 251.4 ± 42.5 | 256.2 ± 44.4 | 263.3 ± 43.9 |
| Cadence (rpm) | 96.9 ± 5.9 | 100.5 ± 6.6 | 91.4 ± 1.4 |

* = significant: UF Rollers vs. Trainer (\(p = 0.021\)) UF Rollers vs. Ergometer (\(p = 0.027\))

Motion analysis: UF rollers consistently displayed greater movement when compared to the trainer and ergometer in all variables measured with the largest differences occurring when
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cmpared to the ergometer. Furthermore, the trainer showed greater movement than the ergometer, but to a lesser extent than the UF rollers (Table 3).

**Table 3.** Kinematic variables for participants at approximately 75\% of VO\textsubscript{2} max (\textit{mean} ± SD), values are the SD of the movements from center mean, where the \textit{mean} = 0. Mediolateral steering is the angle that the handle bars move with respect to the mediolateral axis, relative steering is the angle that the handlebars move with respect to the moving bicycle frame. Lean is the angle by which the bicycle moves from upright. Lateral displacement is bicycle displacement from the mean coordinate of the recorded motion. Yaw is the angle by which the front of the bicycle displaces from the center mean with the back of the bicycle displacing in the opposition direction.

<table>
<thead>
<tr>
<th></th>
<th>UF Rollers</th>
<th>Trainer</th>
<th>Ergometer</th>
<th>% change RvT, RvE, TvE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mediolateral Steering SD (deg)</td>
<td>0.84 ± 0.20</td>
<td>0.16 ± 0.07</td>
<td>0.05 ± 0.03</td>
<td></td>
</tr>
<tr>
<td>Relative Steering SD (deg)</td>
<td>1.37 ± 0.24</td>
<td>0.21 ± 0.05</td>
<td>0.05 ± 0.03</td>
<td></td>
</tr>
<tr>
<td>Lean SD (deg)</td>
<td>0.79 ± 0.13</td>
<td>0.18 ± 0.05</td>
<td>0.05 ± 0.01</td>
<td></td>
</tr>
<tr>
<td>Lateral Displacement of Bicycle SD (cm)</td>
<td>19.7 ± 3.8</td>
<td>1.50 ± 0.40</td>
<td>0.60 ± 0.10</td>
<td></td>
</tr>
<tr>
<td>Yaw SD (deg)</td>
<td>0.64 ± 0.08</td>
<td>0.17 ± 0.02</td>
<td>0.02 ± 0.00</td>
<td></td>
</tr>
</tbody>
</table>

**Discussion**

The present study was the first to investigate the metabolic cost that may be associated with balance on a bicycle in highly-trained cyclists at or near a typical race pace intensity by way of UF rollers. This was done in order to put forth a cycling research methodology that may have better ecological validity where the outcome variables include but are not limited to: metabolic economy, electromyography (EMG), peak power, aerodynamics, and general cycling kinematics. The primary finding was that UF rollers require a statistically significant ($p = 0.015$) increase in VO\textsubscript{2} ($1.2 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$) when compared to the other common cycling modes at the same mechanical power, namely a stationary trainer and an ergometer. This increase in VO\textsubscript{2} averages out over participants tested to be approximately a 9.3 W increase to hold the same VO\textsubscript{2} on the UF rollers versus the cycler ergometer.

**Mechanism:** It is logical to assume that the increase of VO\textsubscript{2} required for the UF rollers is due to the nature of the mode. That is, UF rollers most likely require the rider to utilize
stabilization muscles more, and at a higher frequency and activation force than the other modes tested. In addition, upper extremity and trunk muscles are more active during cycling on UF roller leading to a greater VO$_2$ requirement.

The motion analysis provides strong evidence for this assumption. The lean and yaw of the bicycle and rider have been shown to be a principal component of motion during cycling (11), and therefore, are key components to understanding how riders balance on UF rollers. As a rider leans right or left, he/she remains upright and balanced by either leaning one’s body in the opposite direction relative to the bicycle lean, thereby keeping center of gravity over the contact points of the wheels to the roller’s drums, or by quickly turning into the lean and immediately counter steering to bring their line back towards the center of the rollers (1). Due to the requirement of having the riders remain in the saddle, it was likely they utilized the turn, counter steer method as their primary adjustment action, whereas, if the rider stood up, they would be in a better position to accommodate bicycle lean by body counter lean particularly at higher power outputs.

The utilization of the steer, counter steer method can be further illustrated by the relative steering values being greater than the mediolateral steering values, this is because as the bicycle leans, yaw occurs, followed by the rider turning into the lean to upright the bicycle out of the lean, followed by a counter steer to re-center path on the rollers. The relative steering is greatest at the point of the counter steer because the bicycle’s path is to go off the side of the UF rollers (leading to a fall), so the rider steers back towards the middle creating a relatively larger angle between the steering angle of the handlebars relative to the bicycle. This complex dynamic occurs rapidly and repeats to varying degrees of intensity throughout the ride on the UF rollers,
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therefore requiring consistent and frequent upper extremity and trunk muscle activation to carry out the process.

The results showed some smaller motions during the other modes tested with the trainer’s being greater than the ergometer. The trainer motions did not result in any balance adjustments, instead the rider was held upright in spite of natural lean that occurs during riding. There are some trainers that allow for a more exaggerated lean (http://www.kurtkinetic.com/) with the purpose to feel more natural to the rider, however they still do not require complete balance in the same fashion that UF rollers do. The ergometer was heavier and more stable than the trainer and its motions were closer to that of a vibration, this may change somewhat depending on the model ergometer, but it would not be expected to be drastically different. It was expected that because the trainer allowed for a little more natural motion and because it utilized the rider’s own personal bicycle that it might have lower VO$_2$ values than the ergometer, however this was not the case with the two modes ending up with the same VO$_2$ requirements.

Training implications: The sport of cycling is such, that even very small improvements in performance can be the difference between winning and losing, particularly over a long race. While no specific training research was done, we speculate that UF rollers may have some added training benefits, particularly when technique and mental focus are part of the training. This is based upon the assumption that UF rollers more closely mimic road cycling movements and therefore, the principle of training specificity becomes a factor. Several studies have shown that training with motor control actions similar to the sport is highly beneficial to increasing sport specific VO$_2$ peak and to a lesser extent, sub maximal endurance (3,14). Therefore, UF roller training may be beneficial to incorporate into an endurance training regimen along with power training that is usually done on a trainer.
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Research implications: Given the 1.2 ml·kg⁻¹·min⁻¹ VO₂ difference associated with UF rollers, and the likely mechanism of kinematic changes (balance requirements) being the main source of the difference, one must contemplate if that source, carries over to other types of cycling research. For example, it is not unreasonable to think that EMG patterns may vary on UF rollers versus non balance required modes, and that those differences, though they may be small, may have a significant impact on real world application in training and competition. One may also speculate that even though there was no difference in VO₂ between the trainer and the ergometer that, allowing the rider to use his/her own bicycle for any cycling test could yield more accurate results than the relatively unfamiliar ergometer.

Limitations: The primary limitation to this study was the learning curve associated to riding UF rollers. This was avoided as much as possible by excluding participants who were not proficient and comfortable on rollers. Evidence that the participants were of sufficient skill on UF rollers was that their kinematics were relatively similar at a sub max intensity (75% of VO₂ max). Furthermore, none of the participants fell or had to stop in the middle of testing to regain balance while riding the UF rollers. Another limitation to these results is the fact that there are a plethora of roller, trainer, and ergometer models available to train and perform cycling research on. This limitation was addressed by using a very popular brand and model for each mode. In addition, the fact that power was measured on the bicycle itself suggests that regardless of the brand and model equipment, power would be independently measured therefore increasing the consistency of results.

Future research: Prospective research that considers cycling modality, should seek to verify the results of this study by adding a more clear mechanism behind VO₂ differences found for UF rollers. This may include an in depth analysis of EMG patterns across the three cycling
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modes tested to verify changes in muscle activation for the primary and stabilizer muscle groups in the upper extremities and trunk. Past studies that sought to quantify VO\(_2\) changes, if any that result from cycling position, may warrant revisiting with the use of UF rollers. This is because small VO\(_2\) changes that may have not been statistically significant may have been understated due to the lack of balance requirements and therefore may have different outcomes on UF rollers.

Conclusion: This study showed that riding on UF rollers had a significant effect on metabolic economy requiring an additional 1.2 ml·kg\(^{-1}\)·min\(^{-1}\) VO\(_2\) to ride UF rollers when compared to a trainer or ergometer at the same mechanical power at an intensity of 75% VO\(_2\) peak. This difference equated to approximately 9.3 W of power that can likely be attributed to balance requirements associated with UF rollers. We speculate that the increase in VO\(_2\) is likely due to muscle activation in the upper extremities and the trunk. This was based on the motion analysis, which illustrated clear differences in kinematics that the cyclists displayed while riding UF Rollers. EMG analysis of the aforementioned muscle groups could be used to verify activation differences across the modes tested. The final aim of this study was to advance the methodology of future cycling research as it relates to metabolic economy, training, and kinematics of highly trained cyclists and to perhaps give legitimate reasoning to revisit some past research topics, such as the effect of cycling position on metabolic economy using UF rollers as the mode for testing. Based on the results found in this study, it is recommended that studies involving metabolic economy, electromyography (EMG), peak power, and general cycling kinematics consider using UF rollers as the mode by which testing occurs.
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References


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