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The metabolic cost of balance in Cycling

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Abstract

Ergometers and stationary bicycle trainers are commonly used in laboratories to simulate overground riding. Missing from such instrumentation, however, is any demand for balance and the fraction of the metabolic cost associated with dynamic balance. An alternative training device, rollers, may provide a more ecologically valid simulation of overground riding because dynamic balance is required. The purpose of this study was to compare oxygen consumption (VO_2) at a similar power level during cycling on an ergometer, trainer, and rollers. Highly-trained cyclists (*n* = 7, VO_2 peak = 65 ± 5 mL·kg^{-1}·min^{-1}) performed a VO_2 peak test on a trainer using their own bicycles, followed by 4 min sub-max tests at a power corresponding to 74.1 ± 4.3% of $\dot{V}O_2$ peak on three cycling devices in randomized order. On rollers and stationary trainer, power was measured via a Power Tap SL+ hub and on the ergometer, using resistance. Matching of mechanical power across all 3 modes, as it correlates to VO_2 was accomplished using linear regression based on the $\dot{V}O_2$ peak test. Mean VO_2 values at constant power levels were: rollers = 49.2 ± 5.2, trainer = 48.0 ± 5.2, and ergometer = 48.0 ± 4.8 mL·kg^{-1}·min^{-1}. Riding on rollers required 2.5% greater VO_2 compared to riding a stationary trainer or ergometer at the same mechanical power level ($p < 0.05$). This increase was likely due to the metabolic cost of balance associated with cycling on rollers and suggests that rollers may better simulate the metabolic cost of overground cycling at approximatlye 70% of VO_2 peak

Keywords: cycling, rollers, ergometer, energy expenditure, kinematics

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Introduction

Overground cycling involves mechanical work against air drag forces, rolling resistance, and internal drivetrain friction. In laboratory settings where cycling is typically performed on an ergometer or a stationary bicycle trainer, resistive forces resulting from mechanical instrumentation can be easily adjusted and controlled experimentally. In many regards this provides a satisfactory simulation of overground cycling. However, cycle ergometers and trainers miss some important aspects of riding overground that potentially contribute to the metabolic costs of overground cycling and may affect cycling performance. These factors include the demands of balance and the dynamic interaction of the cycle and human body. Rollers are an alternative training device that demands balance and cycling technique that many riders consider to be closer to overground cycling. Thus from a research perspective, rollers may provide a more ecologically valid laboratory method for measurement of physiological and biomechanical characteristics of cycling, given power can be accurately measured. In this study, rollers were compared against a stationary trainer and ergometer cycling to better elucidate the metabolic costs associated with balance in cycling.

While fixed 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 considered for cycling research to better mimic road cycling conditions where the rider is constantly using minor muscle movements for course correction, balance adjustment, and stabilization. A device stabilizing the trunk has been shown to reduce the metabolic cost of riding on an ergometer, suggesting core muscles play a significant role in consuming energy during cycling (McDaniel, Subudhi and Martin 2005). A similar concept has been investigated in weight lifting, researchers have noted significantly greater ($p < 0.05$) mean electromyographic (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” (McCaw and Friday 1994; Schwanbeck, Chilibeck, and Binsted 2000). This concept carries over to walking as well; Donelan, Shiplman, Kram, and Kup (2004), reported a metabolic reduction during walking when an individual had external balance stabilization in the lateral direction. Cycling over ground allows for lateral and angular movement that can result from the cyclist’s interaction with a frame that is not fixed in position (Hug and Dorel 2009). Controlling or allowing for lateral and angular movement may have an effect on a cyclist’s metabolic economy and ability to produce power. To address these concerns, cycling rollers may be a more appropriate ecological means for studying metabolic economy, via introducing rider balance and, therefore, more closely mimicking road cycling conditions. A motion analysis system can be used to record the bicycle's lateral and angular movements, as well as the directional movements. Differences found in the kinematics could help explain differences 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. Therefore, the purpose of this study was to examine metabolic economy in well-trained cyclists during three cycling modes: (a) rollers, (b) cycle trainer, and (c) cycle ergometer, all at similar mechanical power. It was hypothesized that VO2 and kinematics would differ between the modes, with the rollers requiring a greater metabolic cost and kinematic variability than the other modes at the same mechanical power. By utilizing a motion analysis system, we sought to quantify key bicycle movements such as, bicycle lean, yaw, and steering, for the purpose of offering a logical explanation of any metabolic differences between the modes.

Materials and methods

Participants

Ten subjects were invited to participate in the study based on preliminary recruiting; seven completed the protocol. Seven highly-trained, male cyclists who were proficient on rollers volunteered to participate; they were recruited from local cycling teams and clubs. To determine roller proficiency, each participant gave verbal assurance they felt comfortable and stable on rollers and all had at least 100 hours of rollers experience. This was further validated when none of the participants fell or needed to restart the protocol on the rollers. Each participant had a minimum of 5 years of cycling experience and ranged in United States Cycling Federation categories from 4 to 2. (*see* Table 1 for subject characteristics). This study was approved by the Utah State University IRB and all participants signed a written consent document prior to participating in the study.

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

***n* = 7**	**M ± SD**
Age (years)	30 ± 10
Height (cm)	181 ± 8
Mass (kg)	75 ± 12
$\dot{V}O_2$ peak ($ml \cdot kg^{-1} \cdot min^{-1}$)	65 ± 5
$\dot{V}O_2$ peak ($L \cdot min^{-1}$)	4.9 ± 0.8
Ambient Temperature (°C)	19 ± 1
Altitude (m)	1382

Protocol

All participants performed a warm-up session for a self-selected duration (10 - 30 min) immediately prior to testing. It is not likely the length of the warm up affected the subsequent results, because the subjects were highly trained and knew from experience how much to warm up to optimize performance. Following the warm-up, each participant underwent an incremental graded exercise VO_2 peak test (increase of 50 W per min) in the upright position, remaining in the saddle while riding his own bicycle on a CycleOps^{TM} 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. The trainer mode was selected for a VO_2 peak test because it was a good compromise between rollers and an ergometer, allowing the participants to use their own bicycles while disregarding balance. VO_2 peak was confirmed with a minimum respiratory exchange ratio (RER) of 1.10 and a heart rate that was close to the participant's predicted max (220 – age). Power output was measured during the VO_2 peak test via a Power Tap SL+^{TM} hub which has been shown to be a reliable and valid instrument at the intensities used in this study (Bertucci et al. 2005). The hub sensor calculated torque measurements at 60 Hz, which in conjunction with the wheel angular velocity was used to determine instantaneous mechanical power. These power characteristics were transmitted to the receiver and recorded as 1 Hz averages. The same instrumented wheel was used for all participants for the VO_2 peak tests as well as the subsequent sub-max comparison tests, except the cycle ergometer mode. Prior to all bouts using the instrumented wheel, a calibration was performed by removing all torque applied to the Power Tap and setting it to zero as outlined by the manufacturer. Based on the results of the VO_2 peak test, mechanical power that corresponded to 70% of peak VO_2 was calculated for the sub-max comparisons (Figure 1). The actual power output of the cyclists during testing corresponded with 74.1 ± 4.3% of VO_2 peak. Recovery time after the VO_2 peak test was self-selected by the participant (all > 30 min) with an understanding of the performance requirements that remained in the testing session. The participants were highly trained, aware of their own need for recovery to achieve optimal performance, and we allowed them to individually determine the time needed for recovery before continuing.

Following recovery, each participant began the cycling mode comparison tests on all three modes (Monark ergometer with modified handlebars, saddle, and pedals to better match a road bicycle; CycleOps^{TM} Supermagneto trainer; CycleOps^{TM} aluminum rollers with magnetic resistance) in randomized order. All participants were given their target mechanical power that corresponded to approximately 70% of VO_2 peak and were asked to maintain that power across all three modes being tested and to remain in the saddle throughout. For the rollers and trainer modes, participants were asked to select a gear that equaled their target power at 90 rpm. If necessary, they could adjust rpm to achieve and hold their target power. Power was measured in W via a Power Tap SL+^{TM} hub in conjunction with a Joule Pro^{TM} cycle computer fixed to the handlebar that gave real-time feedback on power output. Resistance was set on the cycle ergometer by adjusting weights that applied friction to the ergometer flywheel to give the appropriate power at 90 rpm.

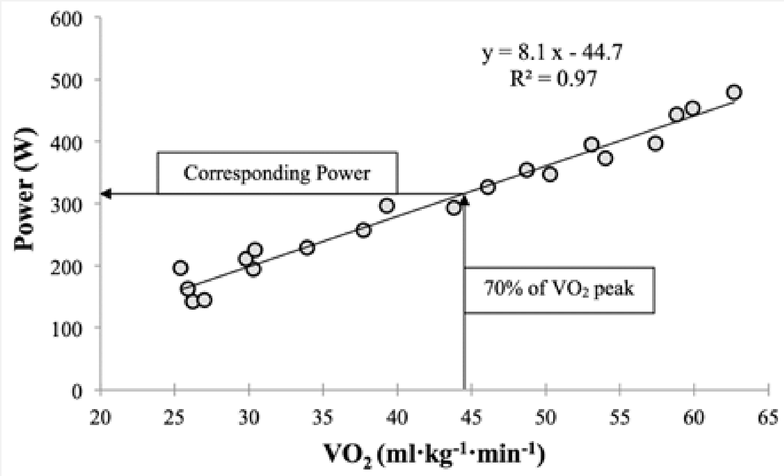

Figure 1. Example of a power versus VO2 graph used to predict power at 70% of VO2 peak using the formula: Power = (70% VO2 peak) • (Slope) + Intercept. The slope of the regression equation was also used to adjust measured VO2 values for roller and ergometer conditions to a power level equal to that for the trainer condition.

While cyclists maintained cadence via a metronome, actual cadence for each cycling mode was determined from position data of foot markers. Prior to the first sub-maximal bout, participant's warmed-up for a self-selected time. Each bout lasted 4 min to obtain steady-state VO_2 on each cycling mode. The first 2 min allowed the participant to find the appropriate gear and cadence, and to get comfortable with the mode being tested. VO_2 was averaged for the last 2 min of each bout and that value was used for the metabolic economy comparison between modes. It was anticipated that power could not be exactly matched between the cycling modes due the difference in how resistance was applied to the cycle. There was also an element of expected human error in perfectly matching power across different modes. Therefore, a regression line based on each individual's $\dot{V}O_2$ peak test (performed on the trainer) was used to interpolate VO_2 values for the roller and ergometer conditions to corresponding values at the mechanical power measured in the trainer condition. This was done by the equation:

$$VO_{2\,(adjusted)} = VO_{2\,(measured)} - [(power_{measured} - power_{trainer}) / slope_{regression}].$$

This method allowed an adjustment to raise or lower $\dot{V}O_2$ values if the participant cycled at a greater or lesser mechanical power than targeted across the different modes.

Motion analysis

Participants and their bicycles were fitted with reflective markers for the purpose of kinematic analysis. A Vicon motion analysis system with seven cameras (T20 model) sampled the movements at a frequency of 100 Hz for 1 min during each mode. Nexus software was used to collect three-dimensional position data. Thirteen markers were placed on each participant, eight markers were placed on the bicycle, and eight markers were placed on the cycle ergometer in locations that best matched the locations on the bicycles (Figure 2). All angular movements were measured in degrees, while the absolute position of the rider and the bicycle were measured in mm. All of these markers in combination allowed determination of the bicycle's absolute position and angular movements, as well as the rider's overall movements (Figure 2).

Figure 2. A) Reflective markers on the bicycle (seat post, seat stays, center handlebar, brake hoods, and front forks); B) Kinematic movements (steering, lean, displacement and yaw)

Statistical Analysis

Statistical package SPSS version 20 was used to run repeated-measures ANOVA with follow-up multiple comparisons (LSD) in order to compare the submaximal $\dot{V}O2$ values across the three cycling conditions; alpha level was set to 0.05.

Results

Metabolic economy and power variables

After adjusting VO_2 to match mechanical power across the three modes, repeated-measures ANOVA revealed a significant difference (F (2,12) = 6.034, p = 0.014) for VO_2 between the three cycling modes. Follow-up multiple comparisons revealed the rollers condition to require significantly greater VO_2 than both the trainer (P = 0.021, Cohen's d = 0.23) and the ergometer (p = 0.024, Cohen's d = 0.23). A greater $\dot{V}O_2$ (i.e., 1.2 $mL·kg^{-1}·min^{-1}$) was observed during rollers versus both the stationary trainer and the ergometer. This equated

Table 2. VO_2 and power variables for participants at 74.1 ± 4.3% of $\dot{V}O_2$ peak (M ± SD).

	Rollers	Trainer	Ergometer
Power (W)	251.4 ± 42.5	256.2 ± 44.4	263.3 ± 43.9
Cadence (rpm)	95.9 ± 4.7	97.2 ± 6.2	91.4 ± 1.4
Measured VO_2 (ml·kg^{-1}·min^{-1})	48.6 ± 5.0	48.0 ± 5.2	49.0 ± 4.3
Adjusted VO_2 (ml·kg^{-1}·min^{-1})	49.2 ± 5.2*	48.0 ± 5.2	48.0 ± 4.8

* Rollers versus Trainer (p = 0.021); Rollers versus Ergometer (p = 0.027)

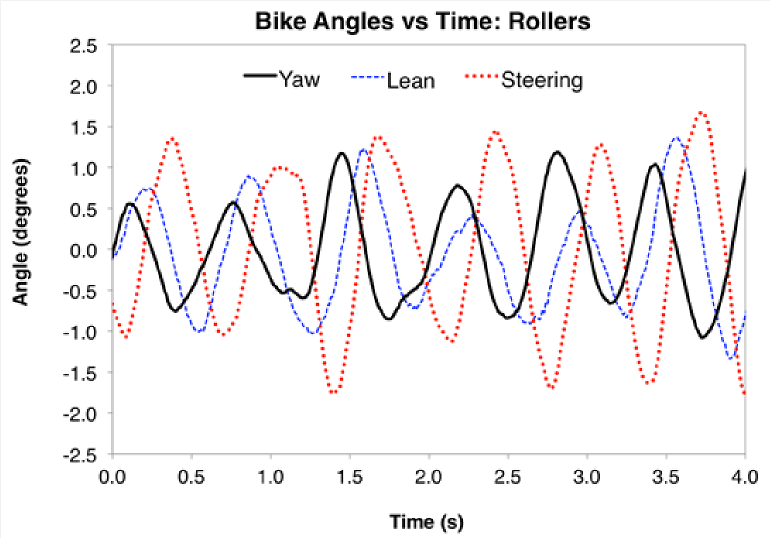

Figure 3. Bicycle angular motion patterns for riding on rollers for a representative rider. Yaw angle was the frame angle with respect to the forward direction in the horizontal plane. Lean angle was the frame inclination with respect to vertical in the frontal plane. Steering angle was the angle of the handlebars with respect to a mediolateral axis in the horizontal plane.

to a 2.5% greater VO_2 requirement for the rollers in order for the rider to maintain the same mechanical power output on the other modes (Table 2). In contrast, the trainer and the ergometer were not different in VO_2 ($p = 0.83$). The mean slope for all participants based on the regression generated from the VO_2 peak test was 7.67 W per mL O_2·kg^{-1}·min^{-1}.

Motion analysis

Angular motion and timing patterns of the bicycle for the rollers condition are shown in Figure 3. Cycle-to-cycle variability was evident as the rider adjusted position around the midpoint of the rollers. Figure 4 illustrates the variability of the yaw, lean and steering angles during one minute of submaximal riding on rollers for a representative rider. The rollers condition consistently involved greater angular and lateral movement compared to the trainer and ergometer in all variables measured (p < 0.001), with the largest differences occurring when compared to the ergometer. Further, the trainer showed greater movement than the ergometer in all variables measured (p < 0.001), but with considerably smaller amplitude than the rollers condition (Table 3).

Discussion

To our knowledge, 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 typical race intensity for a mass-start race. The primary finding was that rollers required a significantly ($p = 0.015$) greater VO_2 requirement (1.2 ml·kg^{-1}·min^{-1}) at the same mechanical power compared to the other common cycling modes of a stationary trainer and an ergometer. This 2.5% difference in VO_2 corresponds to about 9.3 W of mechanical power if oxygen uptake were kept constant on rollers compared to the trainer and ergometer conditions.

Mechanism

It is logical to assume that the greater VO_2 requirement for the rollers is at least in part due the subtle demands associated with balance. That is, rollers require additional muscle activity in the act if stabilization at a higher frequency than the other modes tested. In addition, upper extremity and trunk muscles are likely more active during cycling on rollers leading to a greater VO_2 requirement.

The motion analysis provides strong indirect evidence for this assumption. The lean and yaw of the bicycle and rider have been shown to be principal factors of motion during cycling (Moore , Kooijman , Schwab and Hubbard 2010) and therefore, are key factors to understanding how riders balance on rollers. As a rider leans right or left, he/she remains upright and balanced by either a body lean 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 the line back towards the center of the rollers (Cleary and Mohazzabi 2011).

The utilization of a steer/counter steer method (Cleary and Mohazzabi 2011) can be further illustrated in the current study by the relative steering angles (handlebars relative to frame) being greater than the mediolateral steering

Table 3. Variability of position and angles for the bicycle or ergometer during submaximal riding (M ± SD)

	Rollers	Trainer	Ergometer
Mediolateral Steering SD (°)	0.82 ± 0.17*	0.18 ± 0.07**	0.05 ± 0.02
Relative Steering SD (°)	1.34 ± 0.23*	0.20 ± 0.07**	0.05 ± 0.03
Lean SD (°)	0.77 ± 0.12*	0.18 ± 0.04**	0.05 ± 0.01
Yaw SD (°)	0.62 ± 0.09*	0.15 ± 0.04**	0.02 ± 0.00
Lateral Displacement of Bicycle SD (mm)	20.45 ± 3.0*	1.53 ± 0.26**	0.60 ± 0.12

Values indicate variability about the mean during 1 min of submaximal cycling. Mediolateral steering was the angle of the handlebars with respect to a mediolateral axis of the laboratory coordinate system; relative steering was the angle of the handlebars with respect to the bicycle frame. Lean was the angle of the frame with respect to vertical in the frontal plane. Lateral displacement was frontal plane motion of the bicycle measured at the top of the seat tube of the frame. Yaw was the angle of the frame with respect to straight ahead as measured in the horizontal plane.
* Rollers versus trainer and ergometer for all kinematic measurements (p < 0.001)
** Trainer versus ergometer for all kinematic measurements (p < 0.001)

angles (handlebars relative to straight ahead). The relative steering is greatest at the point of the counter steer because the bicycle's path is aimed to go off the side of the rollers, so the rider steers back towards the middle creating a relatively larger angle between the steering angle of the handlebar relative to the bicycle. This complex dynamic occurs rapidly and repeats to varying degrees of magnitude throughout a ride on rollers. While it is likely that some energy may be conserved in a similar manner to how a pendulum conserves energy, it is probable that some metabolic energy is used for upper extremity and trunk muscle activation to carry out the dynamic balance process.
When cycling in the trainer or ergometer conditions, relatively small angular and lateral motions were observed. The ergometer was more rigidly supported and allowed less motion of the cycle during each pedal stroke; its motions were cyclical at a frequency corresponding to pedal frequency.

Limitations
The primary limitations of this study were not having an identical power measurement device, cycling resistance method, and RPM across the 3 modes. Cycling against the different resistance methods and variation in RPM may have yielded small changes in the crank cycle characteristics or other unforeseen changes in overall cycling and therefore altered the VO_2 (Foss and Halle´n 2004). Conversely, some researchers have reported no significant differences in VO_2 resulting from altering RPM (Lepers et al. 2001). Additionally, these limitations may actually be minimal based on results of the ergometer and trainer having the same adjusted VO_2 despite different resistance methods, power measurement devices and RPM. This suggests these limitations to design were not enough to alter sub-max VO_2 and therefore not significant contributors to the increased VO_2 consumption on the rollers. Another limitation was the learning curve associated with

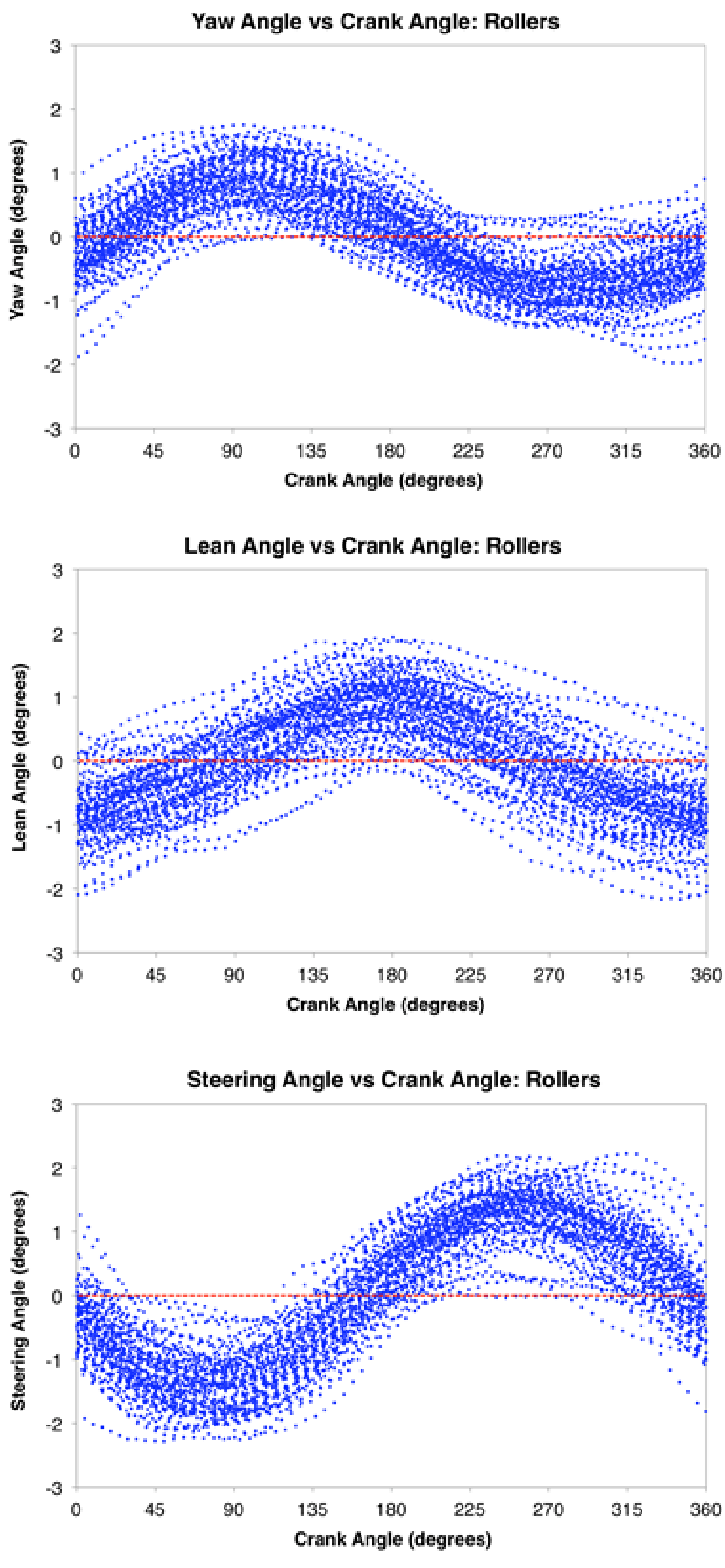

Figure 4. Variability of A) yaw, B) lean and C) steering angles during one minute of cycling on rollers for a representative rider. Approximately 90 crank revolutions are included in these graphs. Positive angles were left of center, negative angles were right of center. Crank angle was 0° with the right pedal at top-dead-center and 180° at bottom-dead-center.

riding rollers. This was avoided as much as possible by excluding participants who were not proficient and comfortable on rollers. None of the participants fell or had to stop in the middle of testing to regain balance while riding the rollers. There are numerous roller, trainer, and ergometer models available for training and cycling research. This was addressed by using a 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 is independently measured, therefore increasing the consistency of results.

Conclusions

This study showed that riding on rollers significantly influenced metabolic economy requiring an additional 1.2 $mL \cdot kg^{-1} \cdot min^{-1}$ VO_2 (2.5%) to cycle on rollers compared to a trainer or ergometer at the same mechanical power and at an intensity of 74.1 ± 4.3 % of VO_2 peak. This difference corresponded to approximately 9.3 W of mechanical power that may be attributed to balance requirements associated with rollers. The clear difference in kinematics between rollers and the other two modes may explain the metabolic difference. These results imply that the exercise intensity obtained from a stationary cycle at a specific workload may not be the same exercise intensity on a bicycle riding over the ground. Based on the results of this study, it is recommended that future research involving metabolic economy, electromyography, and general cycling kinematics consider using rollers as the mode by which testing occurs.

Practical applications

Training implications

The sport of cycling is such that even small improvements in performance can be the difference between winning and losing, particularly in long races. While no specific training research was done, we speculate that rollers may have some added training benefits, particularly when technique and mental focus that are unique to rollers are part of the training. This is based upon the assumption that 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 target sport is highly beneficial to increasing sport specific VO2 peak and to a lesser extent, sub maximal endurance (Fernhall and Kohrt 1990; Roels et al. 2005).

Research implications

Given the approximate 2.5% VO2 difference associated with rollers, and the possible mechanism of increased muscle demand for balance 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 reasonable to speculate that EMG patterns, particularly in the upper extremities and the trunk, may vary on rollers versus non-balance required modes, as has been reported on a treadmill (Arkesteijn, Hopker, Jobson, Passfield 2012).

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 rollers. This may include an in depth analysis of EMG patterns across the three cycling modes to verify changes in muscle activation for the primary and stabilizer muscle groups in the upper extremities and trunk. Use of a cycling treadmill has potential to address ecological concerns of balance during cycling and has been used to successfully measure a variety of typical cycling outcomes (Hagberg, Giese, and Schneider (1978); (Davies 1980); Hagberg, Mullin, Giese and Spitznagel (1981); (Coleman et al. 2007). A cycling treadmill has the advantage of holding the cyclist at near constant speed, however these treadmills are often very large and expensive compared to relatively cheap, portable rollers.

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