Loughborough University

This item was submitted to Loughborough's Research Repository by the author.
Items in Figshare are protected by copyright, with all rights reserved, unless otherwise indicated.

# Model based automated cycling ergometer

PLEASE CITE THE PUBLISHED VERSION

http://dx.doi.org/10.1016/j.proeng.2014.06.030

PUBLISHER

© Elsevier

VERSION

VoR (Version of Record)

PUBLISHER STATEMENT

This work is made available according to the conditions of the Creative Commons Attribution-NonCommercial-NoDerivatives 3.0 Unported (CC BY-NC-ND 3.0) licence. Full details of this licence are available at: http://creativecommons.org/licenses/by-nc-nd/3.0/

LICENCE

CC BY-NC-ND 3.0

REPOSITORY RECORD

Chakravorti, Nandini, Heinz Lugo, Lydia K. Philpott, Paul P. Conway, and Andrew A. West. 2019. “Model Based Automated Cycling Ergometer”. figshare. https://hdl.handle.net/2134/20304.

Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 72 (2014) 180 – 185

Procedia Engineering

www.elsevier.com/locate/procedia

The 2014 conference of the International Sports Engineering Association

# Model Based Automated Cycling Ergometer

N.Chakravorti[a]*, H.L.Lugo[a], L.K.Philpott[a], P.P.Conway[a], A.A.West[a]

[a]*Loughborough University, Loughborough, LE11 3TU,U.K.*

**Abstract**

Laboratory testing of cyclists is currently undertaken using turbo trainers or cycle ergometers. The benefits of laboratory testing are the ability to measure performance: (i) more accurately and repeatedly and (ii) under controlled conditions enabling, for example, video analysis to determine joint-specific power production or enable novel instrumentation to be applied to the bicycle, for example, to measure seat interface pressure. Influence of the bicycle fit on torque production have been presented by Irriberri et al(2008) and Peveler et al(2007). Market leading bicycle ergometer manufacturers, such as Lode and Monark, provide feedback on performance metrics including cadence and force measurement. However, neither ergometer provides real time adaptation of bicycle fit to the resolution (i.e. < mm precision) required by elite athletes or allows adjustments to position whilst cycling under simulated road / track conditions. The objective of the research presented in this paper is to demonstrate and provide initial validation results for a novel, fully automated cycle ergometer that incorporates faster, repeatable and more accurate adjustments to bicycle geometry. The ergometer also allows the cyclist to use their preferred handlebars and saddle to accommodate the different cycling disciplines, e.g. track, road, mountain and BMX. The ergometer enables fitting adjustments to be controlled whilst cycling and aims to reduce initial set-up times for different athletes to about 30 seconds as opposed to 30 minutes (required by the end-users current ergometer instantiations). Instrumented cranks have been fitted to monitor the torque and force generated by the crank movements in 2-axes through 360 degrees of crank motion. The ergometer can be coupled (via a user selectable clutch mechanism) to an AC servo motor within the drive chain which supports the application of models of bicycle performance to the ergometer to enable torque versus position versus speed profiles as derived from road and / or track trials to be readily mapped into the laboratory environment

© 2014 Elsevier Ltd. Open access under CC BY-NC-ND license.

Selection and peer-review under responsibility of the Centre for Sports Engineering Research, Sheffield Hallam University

*Keywords:*Ergometer; power;fitting adjustments

* Corresponding author. Tel.: +441509227677; fax: +0-000-000-0000 .
*E-mail address:* n.chakravorti@lboro.ac.uk

1877-7058 © 2014 Elsevier Ltd. Open access under CC BY-NC-ND license.
Selection and peer-review under responsibility of the Centre for Sports Engineering Research, Sheffield Hallam University
doi:10.1016/j.proeng.2014.06.030

## 1. Introduction

Turbo trainers, rollers, treadmills or cycle ergometers are commonly used training devices to conduct performance based testing of elite cyclists and enable users (coaches, sport scientists or the cyclists) to take measurements of performance, both mechanical and physiological, more accurately, repeatedly, under safe and controlled environments. Performance features measured in a laboratory include adding strain gauges to the handlebars to measure the force exerted by the arms reported by Champoux et al(2004) or measurement of force at the saddle using pressure pads detailed by Potter et al(2008). Turbo trainers, rollers and treadmills require the cyclist to use their own bike to perform tests, whereas a cycle ergometer has to be *fitted* to each individual. Additionally a cycle ergometer also allows changes in bicycle fit to be examined and also permits the integration of instrumentation to measure performance which may be awkward for a normal bicycle due to lack of access or additional wiring. The effects of bicycle geometry fittings on parameters such as force production, torque production and power production have already been reported by Rankin et al(2010), Iriberri et al(2008) and Vrints et al(2011) respectively. However, bicycle geometry fitting is a slow process that can take up anywhere from 30 minutes to several hours, depending on technical skills and precision required, and generally cannot be adjusted whilst cycling.

## 2. User Goals and Test Scenarios

Consultations with end-users identified the need to have a fully automated bicycle ergometer which permits faster, reliable and more accurate fitting adjustments as opposed to 30 minutes as required by current manual fitting techniques. Additional requirements were identified to quantify cycling performance features like torque and force produced at the cranks whilst cycling, the angular velocity at the cranks and the angular position of the cranks. The key requirements (as seen in Table 1) represent the accuracy in the actual positions (mm level), promptness of the automated movements, ability to use personalised handlebars / saddle / pedals and the ability to make small adjustments (mm level) in the fitting while the ergometer is in use, the ability to display meaningful performance metrics (e.g. left/right leg torque, cadence) and the ability to include controllable resistance mechanisms.

Based on the user requirements, a novel cycle ergometer has been designed, allowing automated set-up in seconds via motor controlled actuators. The addition of a motor driven linkage at the cranks has been designed to create a unique system for producing controllable resistance profiles while cycling. A crank sensor has been integrated to monitor performance features such as torque ($\tau$) and force at each crank, the angular velocity ($\omega$) through 360° of crank motion. A torque transducer has also been included to measure the torque generated at the crank axis and is used to validate the torque measured by the crank sensor. Further provisions have been made to support the generation of torque profiles based on models generated from road bicycle trials. This system allows the end-users(cyclist and the researcher) the (1) ability to include performance based cycling power model to replicate the road based trial either by programming the motor driven linkage with actual power/torque values or calculating the different components of the total resistive force the cyclist needs to overcome whilst cycling on the road from the weather and terrain information and (2) the ability to view performance metrics such as power, torque, force and cadence produced at the cranks through 360 degrees of crank motion.

Table 1. Requirements for the ergometer.

| Requirement | Explanation | Test Cases |
|---|---|---|
| Automated fitting adjustments | The ability to have automated movements on the various axes (i.e. Saddle horizontal SH, saddle vertical SV, handlebar horizontal HH and handlebar vertical HV) of the ergometer | Three set of measurements taken to test the variability of the positional adjustments |
| System accuracy | Defines how accurate the actual positions are in comparison to the target positions | Three set of measurements taken to test the variability of the positional adjustments |
| Motion speed | Defines how promptly the target positions are achieved | Three set of measurements taken to test the variability of |

| | | |
|---|---|---|
| | | the time taken to move to target positions |
| Adjustment while in motion | Positional adjustments made whilst the cyclist is cycling | Positional adjustments made whilst the cyclist is cycling |
| Instrumented cranks | Measurements of τ, force and ω through crank rotation. | Measurements of τ and force through crank rotation taken and the τ measured via this sensor is compared to those measured by the torque sensor |
| Constant speed profile | Crank axis is moved at a constant angular speed. | Crank motor is ramped up to a specific speed and the cyclist is asked to drive against the motor. |
| Constant torque profile | Certain torque set points are set and the cyclist is asked to cycle against it | Feedback from the torque sensor or the crank sensors are used to program the motor to follow the cyclist's torque in order to give the ergometer a feel of a "real" cycle. |
| Fit in cycling model | Road trial measurements are used to generate a model of cycling performance | Comparison of the power measured by SRM as opposed to those derived via a mathematical model. |

## 3. Automated Ergometer

Motor controlled actuators are used to facilitate the horizontal and vertical movements on the handlebars and the saddle. Linear rails and lifting columns having accuracy of < 0.1mm are used to achieve positional movements on the handlebars and the saddle. The motion of each unit is controlled by an electric motor (the vertical columns have 3 phase 400V and the horizontal rails have 3 phase 230V motors). Each rail and column is driven to home positions before actual position adjustments are commenced. The crank axis of the ergometer is fitted with a 3-phase AC servo motor and is utilised to replicate user specified resistance profiles e.g. constant angular velocity or torque. Instrumented cranks sensors provided by Beru F1 Systems (2011) are fitted to measure performance features such as force, torque (τ) applied at each pedal and angular velocity at which the cyclist is pedalling through 360° degrees of crank motion(as seen in Fig 1(b)). A torque transducer is fitted in line with the crank axis AC motor to measure the torque produced by the cyclist whilst in motion and is related to the torque measured by

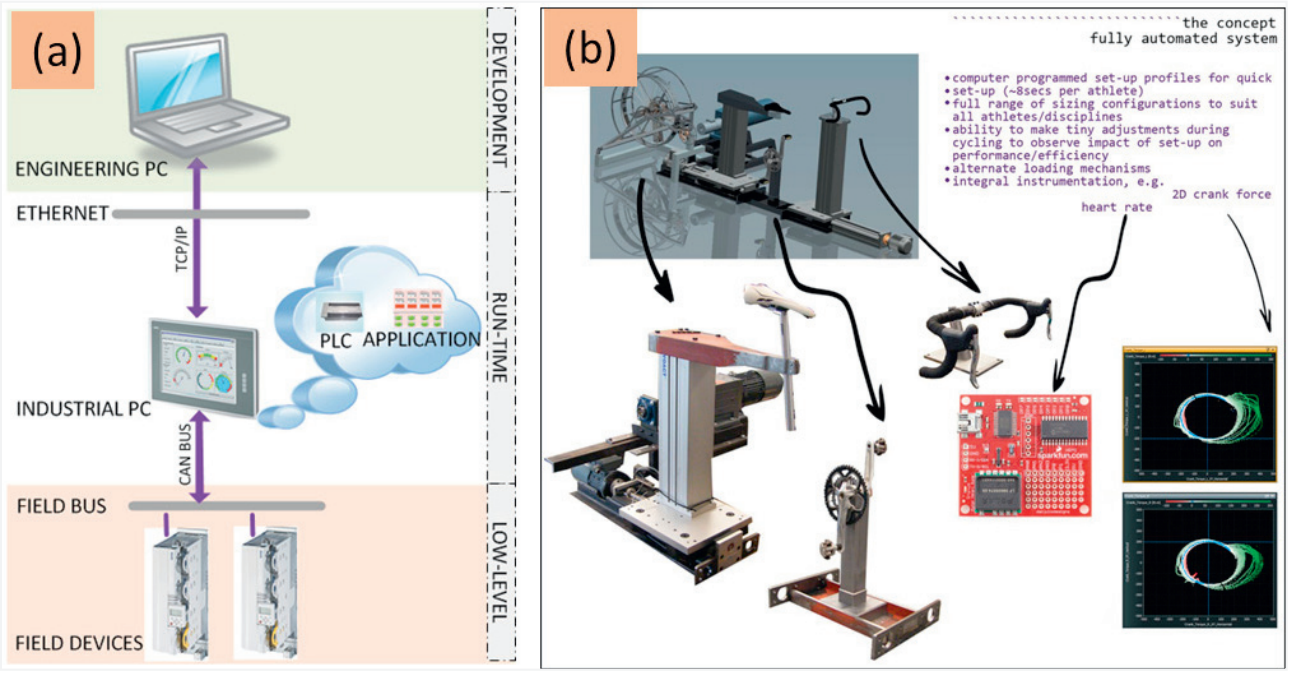



Fig. 1. (a) overview of the system; (b) automated ergometer concept

the crank sensors in accordance to the crank gear ratio.

The handlebars have a fitting diameter of 28.57 mm thus enabling the use of any standard handlebars. Seat-post mounts were also designed to enable the athlete to use their own saddle if desired. The ability to permit the cyclist to use their preferred handlebars and saddle is essential to accommodate the different cycling disciplines, e.g. track, road, mountain bicycle and BMX.

In this system, the user interacts with the ergometer to read / write parameters from / to the drives (for fitting and configuration) and read sensor data via a Human Machine Interface (HMI) application. The software is initially written in a development environment in an Engineering PC and then downloaded to the Industrial PC (IPC) via the Ethernet. The IPC has an integrated Programmable Logic Controller (PLC) and the run-time software application (as seen in Fig 1(a)).

## 4. Cycling Power Model

Cycling performance models have been reported by Davies (1980), Olds et al (1995) and Martin et al (1998). A cycling model reported by Martin et al (1998), has been adapted for this research based on the accuracy of the results (standard error of measurement was 2.7W) reported. This model takes into consideration all the resistive forces experienced by a cyclist on the road i.e. aerodynamic drag, rolling resistance, wheel bearing friction, the rate of change of potential and kinetic energy and the friction in the drive chain. Martin et al's model estimates the aerodynamic drag from data captured using a wind tunnel. In the model reported in this paper, wind resistance is estimated from the frontal area for cyclists (as seen in (1)) and the coefficient of drag (as seen in (2)) using results reported by Heil (2002) for cyclists not using aero-handlebars. (Note: In equations (1) and (2) below $m_b$ is body mass).

$$Area = 0.01929 \times m_b^{0.720} \quad (1)$$

$$DragCoefficient = 4.45 \times m_b^{-0.45} \quad (2)$$

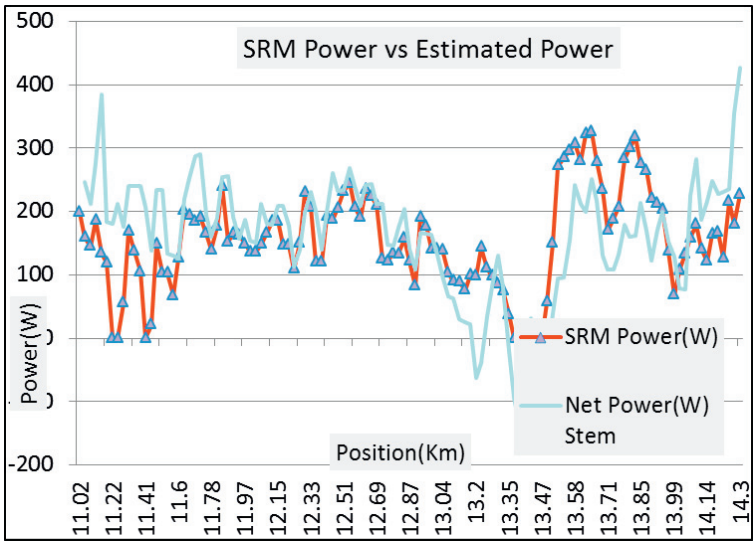



Fig. 2. Comparison of power from road trial versus model

Road cycling trials were conducted using a SRM (Schoberer Rad Messtechnik) Power Measurement System (2013). The SRM unit records the power, cadence and the speed for the ride. For each trial, thde mathematical model was used to estimate the resistive forces based on the air and ground velocity, road terrain, total mass of the system (includes the cycle and the cyclist), and the drag area (as derived from equations (1) and (2)), rolling resistance and frictional losses in the bearings and chain drive system. The potential energy and the rolling resistance values were determined from by the road gradient. Using this model, resistance profiles were generated and programmed in the crank motor demand profile to provide variable resistance at the cranks, the intention of which is to replicate accurately the resistance a cyclist has to overcome for a road trial (see Fig 2).

## 5. Results

Three sets of trials were conducted in different sessions to determine the variation in the actual positions moved by each rail (and column) whilst setting-up the cycling ergometer from the home reference points to an elite cyclist's preferred set-up. The standard error in the mean values for the actual positions of the *saddle horizontal* (SH), *saddle vertical* (SV), *handlebar horizontal* (HH) and *handlebar vertical*(HV) axes for the three sessions is illustrated in Table 3 and highlights a small range variability (x) ($0.011<x<0.155$m) in measurements across different sessions.

Table 2. Time taken by each axes to move from home reference position to desired target positions for trials in different sessions.

| Axes | Avg1(s) | Avg2(s) | Avg3(s) | $\sigma_1$(s) | $\sigma_2$(s) | $\sigma_3$(s) | $\sigma_{m1}$(s) | $\sigma_{m2}$(s) | $\sigma_{m1}$ |
|---|---|---|---|---|---|---|---|---|---|
| SH | 5.7 | 5.53 | 5.6 | 0 | 0.06 | 0.06 | 0 | 0.03 | 0.03 |
| SV | 14.1 | 13.9 | 13.9 | 0.21 | 0.15 | 0.06 | 0.12 | 0.08 | 0.03 |
| HH | 9 | 9 | 8.9 | 0.1 | 0.1 | 0.1 | 0.06 | 0.05 | 0.06 |
| HV | 52.9 | 52.8 | 52.7 | 0.06 | 0.12 | 0.06 | 0.04 | 0.07 | 0.03 |

Table 3. Standard error of mean of actual positions on each axis.

| Sessions | SH | SV | HH | HV |
|---|---|---|---|---|
| 1 | 0.053 | 0.088 | 0.011 | 0.025 |
| 2 | 0.155 | 0.093 | 0.025 | 0.025 |
| 3 | 0.154 | 0.044 | 0.034 | 0.035 |

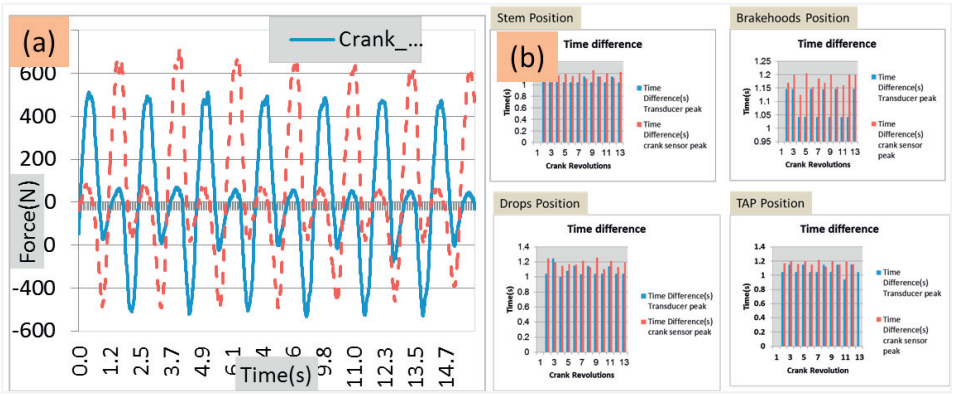



Fig. 3.(a) Radial forces measured at the right and left cranks; (b) Crank revolution indicative times for both measuring sources

The means (*Avg*), standard deviation ($\sigma$) and the standard error of mean ($\sigma_m$) for the time taken to move to the target positions (80mm, 71mm, 136mm and 282mm on SH, SV, HH, HV respectively) from home reference position on the different sessions for each axis are illustrated in Table 2. The maximum time required to move each axis is 52.9 seconds (as seen in Table 2). Moving to different target positions (15mm, 160mm, 202mm and 271mm on SH, SV, HH and HV respectively) from the first set-up is much quicker as the rails and columns have to travel smaller distances. The vertical movement on the saddle needs the maximum time (17.3sec) whilst the vertical movement on the handlebar needs minimum time (i.e. 2.7seconds).Test trials were conducted to measure the torque produced by the cyclist on each crank and the torque measured by the torque transducer in line with the motor driving the crank axis. The crank axis was driven by the motor up to cadence of 25 RPM and then the cyclist was asked to work against the motor (following a constant speed profile as mentioned in Table 1). For these trials the sample refresh rate for the Beru and crank motor torque measuring sources are different i.e. 100ms and 5ms

respectively. The time difference between the peaks for the left side and right torques (as seen in Fig 3(b)) for each series gives an indication of the time taken by the cyclist to go through a revolution. The variability in the time difference can be attributed to the different sampling frequencies for the measurement sources and variation in the synchronisation to mark the start of data capture. The crank sensor measures the force in the radial direction at the cranks and a positive value indicates tension and a negative value indicates compression (as seen in Fig 3(a) – the solid and the dashed lines represent the force measured at the left and right cranks).

## 6. Conclusions

This research enables the customisation of a novel cycling ergometer to support rapid reconfiguration for athlete set-up preferences and the ergometer further allows the inclusion of torque/angular velocity/angular position profiles to replicate road cycling training profiles. The use of the technology presented in this paper can be used to give a competitive edge to elite athletes and also has a potential for low cost manufacture to benefit any serious cyclist if the system architecture and power model are cost effective.

The automated fitting adjustment reduces the set-up time from 30 minutes to about 80 seconds for the first set-up after a power cycle, and about 17 seconds for subsequent set-ups (since the requirement to "home" the axes is only required on power up). The incorporation of the "feel" of cycling within the system requires an accurate model of inertial forces, air and rolling resistance, terrain models and human performance to be incorporated within the crank motor control algorithm. Further cycling trials will be undertaken to improve the consistency between the measured power values and those derived via the mathematical model (most likely attributable to limitation in determining consistent values for rolling and wind resistance in the physical trials). Controllable cycling resistance profiles are readily embedded to ensure that relevant torque and speed profiles are provided to the end-user. Extensive long term trials have been planned to include a range of elite and competitive cyclists to determine the efficacy of the ergometer functionality in supporting increased athlete performance.

## References

Martin JC, Brown NAT. Joint-specific power production and fatigue during maximal cycling. J Biomech 2009;42(4):pp.474-479.

Bressel E, Cronin J. Bicycle seat interface pressure: reliability, validity, and influence of hand position and workload. J Biomech 2005;38(6):pp.1325-1331.

Iriberri J, Muriel X, Larrazabal I. The Bike Fit of the Road Professional Cyclist Related to Anthropometric Measurements and the Torque of de Crank (P242). The Engineering of Sport 7 2008:p.483-488.

Peveler WW, Pounders JD, Bishop PA. Effects of saddle height on anaerobic power production in cycling. The Journal of Strength & Conditioning Research 2007;21(4):1023.

Lode. Lode the Standard in Ergometry. Available at: www.lode.nl. Accessed November 04, 2011.

Monark Exercise AB. Monark Exercise AB. Available at: www.monarkexercise.se. Accessed November 04, 2011.

Champoux Y, Vittecoq P, Maltais P, Auger E, Gauthier B. Measuring the dynamic structural load of an off‐road bicycle frame. Exp Tech 2004;28(3):pp.33-36.

Potter JJ, Sauer JL, Weisshaar CL, Ploeg H, Thelen D. Gender differences in bicycle saddle pressure distribution during seated cycling. Med Sci Sports Exerc 2008;40(6):1126.

Rankin JW, Kwarciak AM, Mark Richter W, Neptune RR. The influence of altering push force effectiveness on upper extremity demand during wheelchair propulsion. J Biomech 2010;43(14):pp.2771-2779.

Vrints J, Koninckx E, Van Leemputte M, Jonkers I. The effect of saddle position on maximal power output and moment generating capacity of lower limb muscles during isokinetic cycling. J Appl Biomech 2011 Feb;27(1):pp.1-7.

Beru F1 Systems. Bf1 Systems. 2011; Available at: http://www.bf1systems.com/. Accessed Dec/2011, 2011.

Davies C. Effect of air resistance on the metabolic cost and performance of cycling. Eur J Appl Physiol Occup Physiol 1980;45(2-3):pp.245-254.

Olds TS, Norton KI, Lowe E, Olive S, Reay F, Ly S. Modeling road-cycling performance. J Appl Physiol 1995;78(4):1596-1611.

Martin JC, Milliken DL, Cobb JE, McFadden KL, Coggan AR. Validation of a mathematical model for road cycling power. Journal of Applied Biomechanics 1998;14:pp.276-291.

Heil DP. Body mass scaling of frontal area in competitive cyclists not using aero-handlebars. Eur J Appl Physiol 2002;87(6):pp.520-528.

SRM. SRM. Available at: http://www.srm.de/index.php?lang=en. Accessed April/11, 2013.