The relationships between cycling economy, pedalling effectiveness and cyclist's musculoskeletal state

Indrek Rannama, Karmen Reinpõld, Kirsti Pedak, Kristjan Port

School of Natural Sciences and Health, Tallinn University, Estonia

ABSTRACT
The purpose of the study was to examine the relationships between road cyclists' musculoskeletal state, pedalling technique and metabolic economy (*Gross Efficiency-GE*) measured during incremental cycling exercise. The strength of knee extensor (KnEX) and flexor (KnFL) muscles of 30 competitive cyclists (19.0±2.1 y.; 1.82±0.06 m; 74.6±6.8 kg) were tested with a *Humac NORM isokinetic dynamometer* at angular speeds 60^0/s (Maximal strength) and 180^0/s (strength endurance and Fatigue Index (FI)). The core stability and for the fundamental movement abilities of cyclists were evaluated with *Functional Movement Screen (FMS)* test battery. After that cyclists performed *incremental cycling exercise* on *Cyclus2 ergometer* using their own racing bike equipped with *Garmin Vector* pedals. The ventilator, pedalling Torque Effectiveness (TE) and Smoothness (PS) parameters were captured continuously during the test. The *GE* was computed as ratio between mechanical cycling power and energy expenditure rate. The FMS score, thigh muscles strength characteristics, as well averaged GE, TE and PS values between aerobic (AeL) and anaerobic (AnL) work levels were registered for analysis in a later stage. Correlation and regression analysis were used to assess the relationships between the registered parameters. Tests revealed a moderate relationship between the GE and cyclists' ability to perform fundamental movements, evaluated by FMS test, as well as with KnEX FI and biomechanically effective pedalling technique. Multiple regression analysis of in-between subjects variation in GE the KnEX FI (Adj. R^2 = 0.36) revealed common explanatory power with TE (Adj. R^2 = 0.19), but adding the FMS score to the both parameters separately will increase the adjusted explanatory power of the model with 4% (Adj. R^2 = 0.40) and 12% (Adj. R^2 = 0.31) for KnEX FI and TE models respectively.

Key words: Gross Efficiency, Isokinetic Dynamometry, FMS test, Incremental Cycling Exercise, Garmin Vector, Cyclus2

Introduction

For a forward movement cyclist must overcome the environmental and rolling resistance and also the force of gravity in uphill cycling (Faria et al., 2005b). This requires from a cyclist to transfer the energy received from the food or stored in the body to the mechanical work (Ettema & Lorås, 2009). When pedalling, the cyclist will do both internal and external mechanical work. The internal mechanical work is done by moving the body segments relative to the body's centre of gravity and to overcome the resistance of different passive tissue and antagonistic muscles within the body, the external work is needed to move the body's centre of gravity, in cycling, mainly to generate forces that move the bicycle forward (Ettema & Lorås, 2009; Minetti, 2011).

Road cycling is considered one of the most energy-demanding sports where high metabolic efficiency is required for the conservation of energy resources (Faria et al., 2015a; Jeukendrup et al., 2000), that is, how much energy can be transformed into external mechanical work and how much energy leaves the body as a heat (Ettema & Lorås, 2009) generated by the result of biochemical and physiological processes (Mady, 2013; Spanghero et al., 2018) and also as a product of internal mechanical work (Minetti, 2011). In the light of the latest knowledge, the most valid and stable feature of the cycling performance assessment is the ratio of the total cost of metabolic energy to the mechanical external work (Gross Efficiency - GE) (Castronovo et al., 2013; Ettema ja Loras, 2009; Moseley & Jeukendrup, 2001) and the GE can explain up to 30% of the variation of the aerobic cycling performance (Jobson et al., 2012). The GE may, according to theoretical calculations, be at least 30% (Ettema & Lorås, 2009; Spanghero et al., 2018), but in experimental studies the GE of competitive cyclists are found to be on average between 18,5-23,5% (De Koning et al., 2012; Hopker et al., 2010; Luhtanen et al., 1987; Moseley et al., 2004). For the world class professional riders, values up to 28% have been measured and in that population the GE is inversely related with VO2max values (Lucia et al., 2002). It is not completely clear what mechanisms and training adaptions describe differences in the metabolic economy but from a morphological point of view, it has been found that more than half of the difference in metabolic economy variations between elite level cyclists can be explained by the proportion of type I muscle fibres in the Vastus Lateralis muscle (Coyle et al., 1992). Also it is found that exercises affecting local muscle performance properties, like maximal strength trainings (Sunde et al., 2010) and endurance training at higher training intensities (Hopker et al., 2009) are beneficial to improve GE. But a question remains if the local strength properties of main muscles involved in the pedalling action can also describe the differences in metabolic economy between cyclists?

The Metabolic economy depends on the intensity of the work to be performed - up to 40% of the VO2max power the GE improves significantly with increasing workload (Ettema & Lorås, 2009), after which improvement rate lessens (Chavarren & Calbet, 1999; Ettema & Lorås, 2009) or discontinues (Moseley et al., 2004), but after respiratory compensation (onset of blood lactate accumulation) threshold the GE starts to decline (Luhtanen et al., 1987). In addition to the workload intensity, the GE level is affected by a number of pedalling technique characteristics like cadence (Chavarren & Calbet, 1999; Hansen et al., 2002; Lucía et al., 2004), bike handlebar height (Gnehm et al., 1997; Grappe et al., 1998) and saddle setup (Price & Donne, 1997; Ferrer et al., 2014). The relationship between biomechanical rationality, determined as force transfer effectiveness from legs to the pedals (Bini et al., 2013; Fonda & Sarabon, 2010), and GE is still not clear. There are studies where cyclists with higher pedalling efficiency have also shown to have better metabolic economy (Zameziati et al., 2006; Leirdal & Ettema, 2011) and for both indicators, higher values have been found among professional riders compared with lower level cyclists (García-López et al., 2016; Lucia et al., 2002). But the existence of a causal relationship is not clear because when the pedalling efficiency is improved by feedback training, the metabolic economy tends to significantly decrease (Korff et al., 2007).

Most of the studies that explore relationships between cyclists' movement technique and cycling metabolic economy have focused on the distribution of pedal forces in the pedalling cycle, while there is evidences that stabilization or destabilization of the cyclist's position have an effect on metabolic cost in cycling (McDaniel et al., 2005; Miller et al., 2013). Also if the cycling workload increases, the weight of the cyclists' upper body is less supported by the saddle and more force is applied to the handlebar (Costes et al., 2015), this will cause larger isometric contraction of upper body muscle to stabilize the position, which can significantly increase energy consumption (Pedersen et al.,

2002). The weakness or tiredness of the trunk muscles may lead to irrational changes in the kinematics of the rider movements (Abt et al., 2007) and this in turn can lead also to additional metabolic costs. However, little is known about the role of the rider's upper body musculoskeletal status and the stability of the riding position in context of metabolic economy.
Therefore, the purpose of the present study was to examine the relationships between road cyclists' musculoskeletal state, pedalling technique and metabolic economy measured during incremental cycling exercise.

Methods
Participants of the current study were 30 competitive junior and U23 male road cyclists (age 19.0±2.1 yrs., height 1.82±0.06 m, body mass 74.6±6.8 kg, VO2max 65.9±4.4 ml/min/kg). All athletes had at least 4 years of focused endurance cycling training and competition experience, and had annual cycling distance above 12000 km during the last season and above 3000 km during preparation period before experiment. The participants were free of injuries and signed an informed consent term in accordance with the principles of the Declaration of Helsinki.
The procedures of the study were conducted during the second half of preparation period and less than 1 month before first cycling competitions. All experimental procedures for one person were made on the same day and protocol consisted of 3 separate tests in the following order: Functional Movement Screen (FMS) tests, incremental cycling exercise and thigh muscles strength tests on isokinetic dynamometer. All cyclists were familiar with test procedures and had performed all tests at least once in the past.
The musculoskeletal status of cyclists was evaluated in two aspects. The *overall functionality of upper body and pelvis region muscles* to stabilize body position and to perform controlled movements was evaluated with the FMS test package (Cook et al., 2014). All 7 FMS test sub-tests were performed after 15 minutes warm up and at least 3 attempts for all exercises were captured by two computer controlled HD web-cameras (frame rate 30 Hz). Recordings were analysed with video analysis software Kinovea 0.8.25 by an experienced (22 years of practice) physical therapist with 7 years of experience with the FMS. The movement quality of all 7 sub-test were evaluated in four point ranking system (0-3) and all sub-tests scores were summed to a total FMS score (Cook et al., 2014) and saved for impending analysis.
The local muscle strength properties of thigh muscle, as main pedalling force producers in submaximal cycling, were evaluated on the Humac Norm isokinetic dynamometer. The test procedure consisted of 2 tests for knee extensors (KnEX) and flexors (KnFL): the maximum strength (Peak Torque- PT [Nm/kg]) of muscle groups (3 trial and 5 testing repetitions) was evaluated at an angular velocity of 60 °/s and at velocity of 180 °/s (3 trial and 20 testing repetitions) were evaluated the strength endurance (Average Torque of 20 repetitions between knee flexion angle of 30 and 70 degree- AvT [Nm/kg]) and resistance to fatigue measured by Fatigue Index (FI= 100*Average Torque of last 5 reps./ Average Torque of first 5 reps. [%]). The subjects were instructed to start strength endurance test with maximum effort. For both tests left and right leg were tested in a randomised order between subjects and the average values of both sides of each parameter were saved for analysis.
Experimental cycling exercise was performed using the cyclist's personal racing bike mounted on the Cyclus 2 ergometer and bicycle was equipped with pair of Garmin Vector™ power meter pedals. Exercise protocol consisted of a 10 minutes warm-up of steady ride at the power level of 100 W and was followed by the incremental cycling exercise conducted in sitting position hands on the drops: target cadence 90±5 revolution/min (rpm), initial workload of 100 W and the workload increased by 25 W after every 2 minute until exhaustion. During and after 3 minute of the cycling exercise the heart rate and

breath by breath pulmonary O2 (Vo2), CO2 production ($\dot{V}co2$), and expired minute ventilation ($\dot{V}E$) were measured continuously with the Cosmed Quark CPET metabolic analyser (Rome, Italy). The maximal aerobic peak power (PP) and ventilatory threshold levels assessments were performed using Cosmed PFT Ergo software independently by two experienced researchers. The first (aerobic level – AeL) and second ventilatory thresholds level (Anaerobic level – AnL) were estimated by methods described and validated by Weston and Gabbett (2001). The maximal aerobic oxygen uptake ($VO2_{max}$ [ml/min/kg]) was determined as the highest 30 s average values during the exercise. Furthermore, for the future analysis power data at the AeL, and AnL were registered. When the certain intensity level was achieved during first 30 sec of the incremental step the previous increment was chosen as a true value. The values of oxygen uptake (VO2 [ml/min/kg]) and power (P [W/kg]) were normalized with body mass. For the last minute of every step between AeL and AnL the GE (%) value was computed as ratio between cycling power and metabolic energy expenditure rate (Emet). The metabolic energy expenditure rate was computed according to the formula: Emet=[(3.869*VO2)+(1.195*VCO2)]*69.77 (Moseley & Jeukendrup, 2001). To reduce the effect of slow component of VO2, the average value of GE of all steps between AeL and AnL was computed and saved for the future analysis.
The biomechanical effectiveness of force delivery during pedalling was described by Torque Effectiveness (TE=100*(Positive Torque in pedalling cycle)/(Positive + Negative Torque in pedalling cycle) [%]) and Pedalling Smoothness (PS=100*Average Torque in pedalling cycle/Maximal Torque in pedalling cycle [%]), that were registered with Garmin Vector™ pedals. Similarly with GE characteristic, the TE and PS values of second minute of every step between AeL and AnL were averaged and the average values of the right and left pedal were taken into further analysis.
Statistical data analysis was performed with software SPSS version 23.0 (IBM Company, New York). Descriptive statistics were computed for all variables and for every test phase and expressed mainly as a mean ± SD. To describe the intra cyclists' homogeneity in measured parameters the Variability Coefficient was computed as ratio between SD and mean in percent (%). All the data was tested for their normal distribution (Kolmogorov-Smirnov test). Pearson product-moment (for normally distributed variables) or Spearman rank correlation (for non-normally distributed variables) and simple and multiple stepwise regression analysis were performed to examine the relationship between measured parameters. Significance level for correlation analyses was set at $p<0.05$ ($r>|0.36|$). In multiple stepwise regression analysis the significance level for parameter entering was set at $p<0.05$ and removal level at $p<0.1$.

Results

The average values of cycling specific abilities of study subjects were: P_{AeL} - 3.31±0.30 W/kg, P_{AnL}- 4.42±0.35 W/kg, PP - 5.07±0.39 W/kg, $VO2_{AeL}$ – 49.6±4.3 ml/min/kg, $VO2_{AnL}$ - 60.7±4.8 ml/min/kg, $VO2_{max}$ 65.9±4.4 ml/min/kg, GE - 20.6±1.0 % (18.9-22.3%). The descriptive statistics of the musculoskeletal functional abilities and pedalling technique characteristics among the participated cyclists and correlation with GE of those parameters are given in Table 1 below. For FMS test the median value was 15 points and 9 cyclists performed the test under that critical 15 point level. The parameters with highest variability among cyclists were KnEX and KnFL strength and local strength endurance characteristics, while the smallest variation was found in pedalling technique and FI parameters. Said less varying characteristics were correlated with GE. The more fatigue resistant were the KnEx muscles and the better was cyclists' ability to perform fundamental movements as measured by FMS score as well as higher pedalling effectiveness and smoothness were all related with better metabolic economy in cycling

(GE) (Table 1). The more detailed and illustrated information about relationships between named parameters and GE is presented in regression models in Figure 1. No significant correlations were found between GE and thigh muscles strength values (Table 1).

Table 1. The descriptive statistics and correlation with GE of FMS test, tigh muscles strength tests and pedalling technique characteristics

N=30	Minimum	Maximum	Mean	SD	Var. Coef. (%)	Correl. with GE
FMS score (points)	11	18	14.8	1.5	10.4	0.49*
KnFL PT (Nm/kg)	1.40	2.50	1.91	0.26	13.4	-0.19
KnEX PT (Nm/kg)	2.30	4.00	3.10	0.44	14.2	0.00
KnFL AvT (Nm/kg)	0.70	1.20	0.97	0.15	15.1	-0.06
KnEX AvT (Nm/kg)	1.30	2.10	1.66	0.20	12.1	0.19
KnFL FI (%)	58.2	76.7	68.6	5.0	7.3	0.34
KnEX FI (%)	72.1	84.4	77.2	3.5	4.6	0.62*
PE (%)	77.6	94.6	85.7	4.4	5.2	0.47*
PS (%)	22.2	32.2	25.5	2.2	8.4	0.36*

*. Correlation is significant at the 0.05 level (2-tailed).

The correlation matrix (Table 2) describes relationships between musculoskeletal state and pedalling effectiveness parameters. Test revealed a moderate positive correlation between pedalling TE and PS and thigh muscles AvT and FI characteristics. Also there is a moderate inter-correlation between most of those parameters that correlate with GE, except between FMS score and pedalling variables. To test the communality of explanatory power for GE inter subjects' variation of those parameters the multiple regression analysis was performed.

Table 2. Correlations between FMS test score, tight muscles performance values and pedalling technique characteristics

FMS score (points)	1								
KnFL PT (Nm/kg)	-0.34	1							
KnEX PT (Nm/kg)	-0.19	0.68**	1						
KnFL AvT (Nm/kg)	-0.11	0.69**	0.36*	1					
KnEX AvT (Nm/kg)	0.02	0.59**	0.69**	0.62**	1				
KnFL FI (%)	0.25	0.11	-0.11	0.46*	0.20	1			
KnEX FI (%)	0.44*	-0.02	0.02	0.12	0.49**	0.42*	1		
TE (%)	0.29	0.24	0.36*	0.21	0.49**	0.46*	0.57**	1	
PS (%)	0.07	0.38*	0.36	0.23	0.50**	0.44*	0.54**	0.77**	1

*. Correlation is significant at the 0.05 level (2-tailed). **. Correlation is significant at the 0.01 level (2-tailed).

By adding pedalling TE and PS variables separately to the regression model of KnEX FI to explain between subjects variation in GE, both model components did not reveal statistically significant relationship and adjusted R^2 of initial model reduced from 0.36 to less than 0.33. It means that those independent variables share common explanatory power to GE. When combining FMS score with KnEX FI into the same model the explanatory power for GE increases from 36% to 40% and the model is:

$$GE=0.14*KnEX\ FI+0.18*FMS+6.90;\ (R^2 = 0.44;\ adj.\ R^2 = 0.40;\ p<0.001).$$

By combining FMS score into TE model the explanatory power increased from 19% (TE alone) or 21% (FMS score alone) to 31% and the model is:

$$GE=0.08*TE+0.26*FMS+9.85; (R^2 = 0.36; adj. R^2 = 0.31; p=0.003).$$

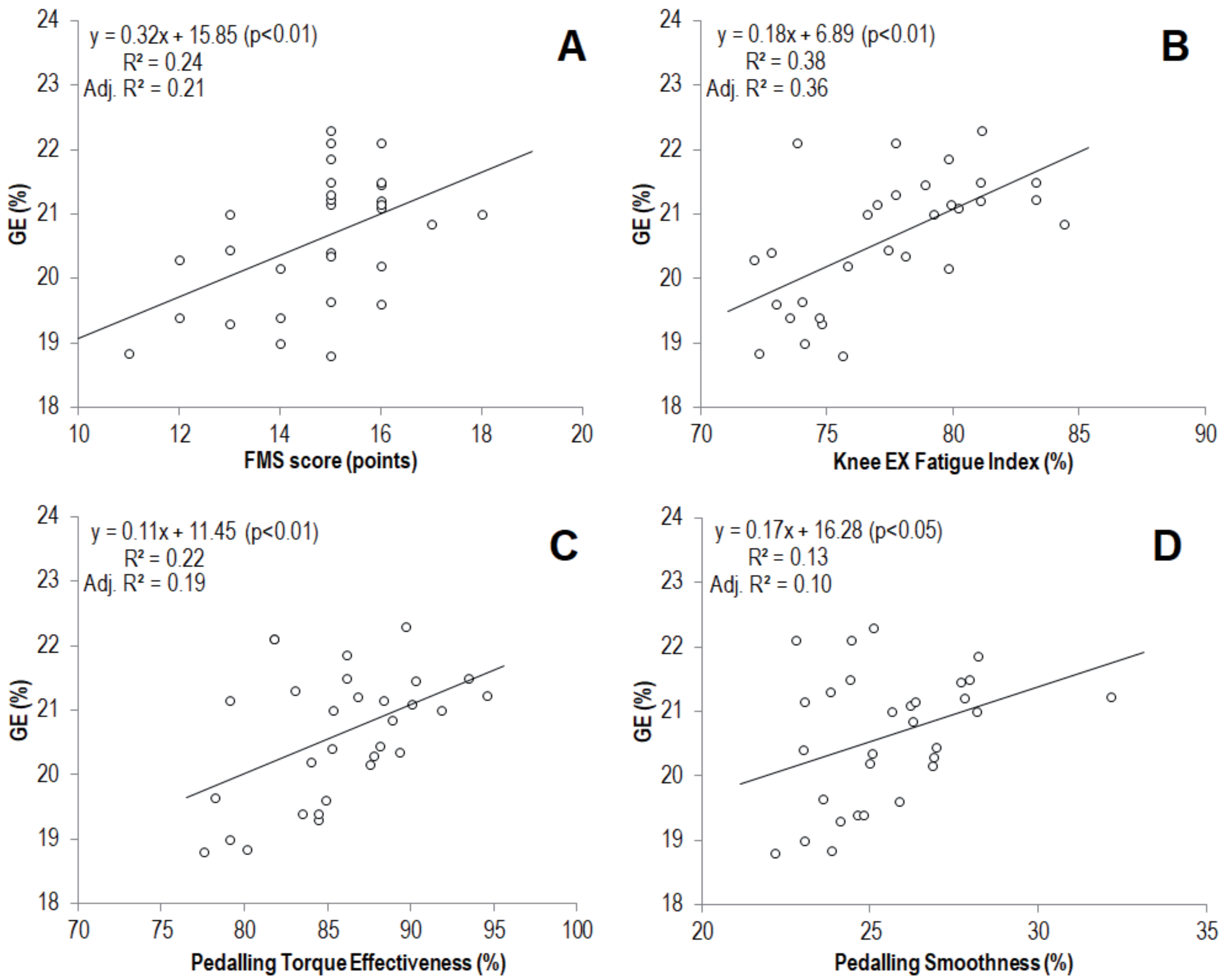

Figure 1. Simple regression between GE and FMS score (A), Knee EX FI (B), Pedalling TE (C) and PS (D)

Discussion

The one aim of present study was to evaluate the musculoskeletal state and cycling specific aerobic performance of young competitive road cyclists. The FMS score, that reflects cyclist's core stability and ability to perform fundamental movements, indicated that almost one third of study subjects achieved scores below 15 points, indicating raised injury risk level (Kiesel et al., 2007; Hotta et al., 2015). The average values found in current study were a bit higher (14.8±1.5) than a results of our previous research conducted in the transition period after the competitive cycling season (14.1±1.8) (Rannama et al., 2016) and results of same aged competitive male runners (14.1±2.3) (Hotta et al., 2015).

The GE values of cyclists in present study were between 18.9-22.3% (average 20.6±1.0%) and this fits well with previous findings (18.5-23.5%) measured in competitive road cyclists (De Koning et al., 2012; Hopker et al., 2010; Moseley et al., 2004), but is significantly lower than is reported amog top level professional riders (Lucia et al., 2002). Also the pedalling TE values (77.6±94.6) at the intensive aerobic cycling workload are similar with previously reported results of trained cyclists (García-López et al., 2015).

The second and main aim of present study was to examine the relationships between cyclists' musculoskeletal state, pedalling technique and metabolic economy during intensive aerobic work, measured during the incremental cycling exercise. Some of the previous studies have shown that cyclists with higher pedalling efficiency have better metabolic economy (Zameziati et al., 2006; Leirdal & Ettema, 2011). Our findings were in agreement with the same trend. However, GE was more strongly related with cyclists' state of the musculoskeletal characteristics. The KnEX FI had largest descriptive power (40%) describing in-between subjects variability in metabolic economy. The earlier studies have not directly shown a link between GE and thigh muscles strength and endurance properties, but the significant morphological factor that seem to describe about a half of the GE variation is the proportion of the Type-I (slow-twitch) muscle fibres in the *Vastus Lateralis* muscle (Coyle et al., 1992). The topic is not settled as an earlier study of Thorstensson & Karlsson (1976) demonstrated that proportional distribution of Type-I and Type-II muscle fibres in the *Vastus Lateralis* correlates strongly (r=0.86) with decline in force during a multi-repetition knee extensors isokinetic exercise at velocity 180°/s. Therefore the causal relationship between KnEX FI and GE in application for cyclists' performance evaluation needs further investigation with intra subjects study design.

The KnEX FI and some other thigh muscles strength characteristics in current study correlated positively with pedalling efficiency and multiple regression analysis revealed that pedalling characteristics do not add any additional descriptive power to KnEX FI. This may indicate that the link between metabolic and biomechanical rationality relationship is buried in some common morpho-physiological properties of KnEX, as themost exploited and trained muscle in pedalling motion (Elmer et al., 2011). This may also explain the tendency among higher level professional cyclists who demonstrate higher values in both metabolic and biomechanical rationality compared to lower tier riders (García-López et al., 2016; Lucia et al., 2002). One interesting findings of our study was that the maximal strength and strength endurance values of thigh muscles were not related to GE. The finding deviates from findings of positive effect of strength training on GE (Sunde et al., 2010). The inter-subjects design of the present study and the local muscle testing (ignoring the inter-muscular coordination) may be not enough sensitive and adequate test to expose the effect of maximal strength on GE.

One of the main findings of this study was that the state of cyclist's core stability and the ability to perform fundamental movements is related to GE and to the states of stabilizing muscles of trunk and pelvis region while the lack of hip and trunk mobility can negatively affect cycling performance. Earlier studies have shown that lower FMS score is related to larger postural swaying during cycling effort (Rannama et al., 2017) whereas a more stable upper body position is related to savings in the metabolic cost (McDaniel et al., 2005). Also less developed muscles fatigue sooner and tiredness of trunk muscles leads to altered upper body kinematics (Abt et al., 2007). All this adds to extra internal mechanical work, that is further related with longer motion paths of the body segments and excessive external mechanical work that is performed by moving body COG against bicycle (Minetti, 2011). To the best of our knowledge, relationship between the general functional movement abilities and the cycling economy has not been previously presented.

Conclusion

The results of the current study demonstrated that during intense aerobic part of the incremental cycling exercise the strongest predictors of metabolic economy were cyclists' ability to perform fundamental movements, evaluated by FMS test and knee extensors resistance to fatigue. The smoother and effective pedalling technique was also positively related with higher metabolic economy, but those pedalling measures are sharing common explanatory power with KnEX strength and fatigue resistance properties.

References

1. Abt, J. P., Smoliga, J. M., Brick, M. J., Jolly, J. T., Lephart, S. M., & Fu, F. H. (2007). Relationship between cycling mechanics and core stability. *Journal of Strength & Conditioning Research*, *21*(4), 1300-1304.
2. Bini, R., Hume, P., Croft, J. L., & Kilding, A. (2013). Pedal force effectiveness in Cycling: a review of constraints and training effects. Journal of Science and Cycling 2(1), 11-24.
3. Castronovo, A. M., Conforto, S., Schmid, M., Bibbo, D., & D'Alessio, T. (2013). How to assess performance in cycling: the multivariate nature of influencing factors and related indicators. *Frontiers in physiology*, *4*, 1-10. doi: 10.3389/fphys.2013.00116.
4. Chavarren, J., & Calbet, J. A. L. (1999). Cycling efficiency and pedalling frequency in road cyclists. *European journal of applied physiology and occupational physiology*, *80*(6), 555-563.
5. Cook, G., Burton, L., Hoogenboom, B. J., & Voight, M. (2014). Functional movement screening: the use of fundamental movements as an assessment of function-part 1. *International journal of sports physical therapy*, *9*(3), 396-409.
6. Costes, A., Turpin, N. A., Villeger, D., Moretto, P., & Watier, B. (2015). A reduction of the saddle vertical force triggers the sit–stand transition in cycling. *Journal of biomechanics*, *48*(12), 2998-3003
7. Coyle, E. F., Sidossis, L. S., Horowitz, J. F., & Beltz, J. D. (1992). Cycling efficiency is related to the percentage of type I muscle fibers. *Medicine and science in sports and exercise*, *24*(7), 782-788.
8. De Koning, J. J., Noordhof, D. A., Lucia, A., & Foster, C. (2012). Factors affecting gross efficiency in cycling. *International journal of sports medicine*, *33*(11), 880-885.
9. Elmer, S. J., Barratt, P. R., Korff, T., & Martin, J. C. (2011). Joint-Specific Power Production during Submaximal and Maximal Cycling. *Medicine & Science in Sports & Exercise*, *43*(10), 1940-1947.
10. Ettema, G., & Lorås, H. W. (2009). Efficiency in cycling: a review. *European journal of applied physiology*, *106*(1), 1-14.
11. Faria, E. W., Parker, D. L., & Faria, I. E. (2005a). The science of cycling: physiology and training-part 1. *Sports Medicine-ADIS International*, *35*(4), 285-312.
12. Faria, E. W., Parker, D. L., & Faria, I. E. (2005b). The science of cycling: factors affecting performance-part 2. *Sports Medicine-ADIS International*, *35*(4), 313-338.
13. Ferrer-Roca, V., Bescós, R., Roig, A., Galilea, P., Valero, O., & García-López, J. (2014). Acute effects of small changes in bicycle saddle height on gross efficiency and lower limb kinematics. *The Journal of Strength & Conditioning Research*, *28*(3), 784-791.
14. Fonda, B., & Sarabon, N. (2010). Biomechanics of cycling. *Sport Science Review*, *19*(1-2), 187-210.
15. García-López, J., Díez-Leal, S., Ogueta-Alday, A., Larrazabal, J., & Rodríguez-Marroyo, J. A. (2016). Differences in pedalling technique between road cyclists of different competitive levels. *Journal of sports sciences*, *34*(17), 1619-1626.
16. Gnehm, P., Reichenbach, S., Altpeter, E., Widmer, H., & Hoppeler, H. (1997). Influence of different racing positions on metabolic cost in elite cyclists. *Medicine and science in sports and exercise*, *29*(6), 818-823.
17. Grappe, F., Candau, R., Busso, T., & Rouillon, J. D. (1998). Effect of cycling position on ventilatory and metabolic variables. *International journal of sports medicine*, *19*, 336-341.
18. Hansen, E. A., Andersen, J. L., Nielsen, J. S., & Sjøgaard, G. (2002). Muscle fibre type, efficiency, and mechanical optima affect freely chosen pedal rate during cycling. *Acta Physiologica*, *176*(3), 185-194.
19. Hopker, J., Jobson, S., Carter, H., & Passfield, L. (2010). Cycling efficiency in trained male and female competitive cyclists. *Journal of sports science & medicine*, *9*(2), 332.
20. Hopker, J., Passfield, L., Coleman, D., Jobson, S., Edwards, L., & Carter, H. (2009a). The effects of training on gross efficiency in cycling: a review. *International journal of sports medicine*, *30*(12), 845-850.
21. Hotta, T., Nishiguchi, S., Fukutani, N., Tashiro, Y., Adachi, D., Morino, S., ... & Aoyama, T. (2015). Functional Movement Screen for Predicting Running Injuries in 18-to 24-Year-Old Competitive Male Runners. *The Journal of Strength & Conditioning Research*, *29*(10), 2808-2815.1
22. Jeukendrup, A. E., Craig, N. P., & Hawley, J. A. (2000). The bioenergetics of world class cycling. *Journal of Science & Medicine in Sport, 3*(4), 414-433.

23. Kiesel, K., Plisky, P. J., & Voight, M. L. (2007). Can serious injury in professional football be predicted by a preseason functional movement screen. *North American Journal of Sports Physical Therapy*, *2*(3), 147-158.
24. Korff, T., Romer, L. M., Mayhew, I. A. N., & Martin, J. C. (2007). Effect of pedaling technique on mechanical effectiveness and efficiency in cyclists. *Medicine & Science in Sports & Exercise*, *39*(6), 991-995.
25. Leirdal, S., & Ettema, G. (2011). The relationship between cadence, pedalling technique and gross efficiency in cycling. *European journal of applied physiology*, *111*(12), 2885-2893.
26. Lucia, A., San Juan, A. F., Montilla, M., CaÑete, S., Santalla, A., Earnest, C., & PÉrez, M. (2004). In professional road cyclists, low pedaling cadences are less efficient. *Medicine & Science in Sports & Exercise*, *36*(6), 1048-1054.
27. Lucia, A.., Hoyos, J., PÉrez, M., Santalla, A., & Chicharro, J. L. (2002). Inverse relationship between VO2max and economy/efficiency in world-class cyclists. *Medicine & Science in Sports & Exercise*, *34*(12), 2079-2084.
28. Luhtanen, P., Rahkila, P., Rusko, H., & Viitasalo, J. T. (1987). Mechanical work and efficiency in ergometer bicycling at aerobic and anaerobic thresholds. *Acta Physiologica*, *131*(3), 331-337.
29. Mady, C. E. K. (2013). Human body exergy metabolism. *International Journal of Thermodynamics*, *16*(2), 73-80.
30. McDaniel, J., Subudhi, A., & Martin, J. C. (2005). Torso stabilization reduces the metabolic cost of producing cycling power. *Canadian journal of applied physiology*, *30*(4), 433-441.
31. Miller, A. I., Heath, E. M., Bressel, E., & Smith, G. A. (2013). The metabolic cost of balance in Cycling. *Journal of Science and Cycling*, *2*(2), 20.
32. Minetti, A. E. (2011). Bioenergetics and biomechanics of cycling: the role of 'internal work'. *European journal of applied physiology*, *111*(3), 323-329.
33. Moseley, L., & Jeukendrup, A. E. (2001). The reliability of cycling efficiency. *Medicine and science in sports and exercise*, *33*(4), 621-627.
34. Moseley, L., Achten, J., Martin, J. C., & Jeukendrup, A. E. (2004). No differences in cycling efficiency between world-class and recreational cyclists. *International journal of sports medicine*, *25*(5), 374-379.
35. Pedersen, P. K., Sørensen, J. B., Jensen, K. U. R. T., Johansen, L. A. R. S., & Levin, K. L. A. U. S. (2002). Muscle fiber type distribution and nonlinear. VO (2)-power output relationship in cycling. *Medicine and science in sports and exercise*, *34*(4), 655-661.
36. Rannama, I., Pedak, K., Bazanov, B., & Port, K. (2017). Cycling specific postural stability during incremental exercise. The relationship with cyclists functional movement screen score. *Journal of Human Sport and Exercise*, *12*(1).
37. Rannama, I., Pedak, K., Reinpõld, K., & Port, K. (2016). Pedalling technique and postural stability during incremental cycling exercise–relationship with cyclist FMS TM score. LASE *Journal of Sports Science*, *7*(1), 3-20.
38. Spanghero, G. M., Albuquerque, C., Lazzaretti Fernandes, T., Hernandez, A. J., & Keutenedjian Mady, C. E. (2018). Exergy Analysis of the Musculoskeletal System Efficiency during Aerobic and Anaerobic Activities. *Entropy*, *20*(2), 119.
39. Sunde, A., Støren, Ø., Bjerkaas, M., Larsen, M. H., Hoff, J., & Helgerud, J. (2010). Maximal strength training improves cycling economy in competitive cyclists. *Journal of Strength & Conditioning Research*, *24*(8), 2157-2165.
40. Thorstensson, A., & Karlsson, J. (1976). Fatiguability and fibre composition of human skeletal muscle. *Acta Physiologica*, *98*(3), 318-322.
41. Weston, S. B., & Gabbett, T. J. (2001). Reproducibility of ventilation of thresholds in trained cyclists during ramp cycle exercise. *Journal of Science and Medicine in Sport*, *4*(3), 357-366.
42. Zameziati, K., Mornieux, G., Rouffet, D., & Belli, A. (2006). Relationship between the increase of effectiveness indexes and the increase of muscular efficiency with cycling power. *European journal of applied physiology*, *96*(3), 274-281.