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The influence of 3D kinematic and electromyographical parameters on cycling economy

JONATHAN SINCLAIR*, JACK HEBRON, STEPHEN ATKINS, HOWARD HURST, PAUL J. TAYLOR

University of Central Lancashire.

Purpose: Economy is considered to be a key factor for the determination of performance in endurance events such as cycling. There have been no investigations which have related cycling economy to simultaneous measurements of 3D kinematics and muscular activation. This study examined selected biomechanical and neuromuscular parameters which have the strongest association with cycling economy. Methods: Twenty-five trained cyclists (31.27 ± 3.19 years) completed steady state cycling time trials at a workload of 180 W. Simultaneous measurements of 3D kinematics and electromyographical parameters were obtained. Continuous measurements of expired gases were used to provide a measure of cycling economy.

Results: A multiple regression analysis showed that key parameters of peak knee extension velocity and mean activity of the rectus femoris muscles were significant predictors of VO_2 during steady state cycling ($P < 0.01$).

Conclusion: This study has documented the key biomechanical parameters pertinent to cycling economy. As economy has been shown to influence aerobic performance, future work should focus on optimising these parameters to improve cycling economy.

Key words: *cycling, economy, VO_2*

1. Introduction

In sports science, economy reflects the amount of inspired oxygen (VO_2) required to maintain a given velocity or power output. It is considered to be a key factor for the determination of performance in endurance events such as cycling (Coyle et al. [5]). As such it is proposed that improvements in economy would be of significant value to cyclists wishing to improve performance.

The factors that influence cycling economy have been examined extensively in biomechanical/physiological analyses (Camara et al. [2]; Coyle et al. [6]; Loveless et al. [14]; Lucia et al. [15]; Moseley et al. [17]; Sunde et al. [22]). Coyle et al. [6] examined the influence of muscle fibre composition on the oxygen (O_2) cost of cycling at a pre-set workload. They concluded that the extent of aerobic type I fibres was strongly related to the O_2 cost of cycling. Thus athletes with a predominance of type I fibres are considered more efficient, potentially as a function of the lower ATP turnover whilst performing steady state exercise. Camara et al. [2] investigated the effects of pedalling technique on cycling efficiency, both at and below the aerobic threshold, using trained cyclists. They found that below the aerobic threshold there was no relation between pedalling technique and cycling efficiency. However, above the aerobic threshold they observed significant correlations between mean torque and evenness of torque distribution. Furthermore, a negative relationship was found between cadence and efficiency. They concluded that intensity plays an important role in the relationship between pedalling technique and cycling efficiency.

Despite the potential to optimise cycling performance, via the manipulation of technical and efficiency parameters, to date there have been no investigations relating cycling economy to simultaneous measurements of 3D kinematics and muscular activation parameters. Therefore, the aim of the current investigation is to examine the biomechanical and neuro-

* Corresponding author: Jonathan Sinclair, University of Central Lancashire, Darwin Building 217, School of Sport Tourism and Outdoors, PR1 2HE Preston, United Kingdom. Tel: 01772253585, e-mail: jksinclair@uclan.ac.uk

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muscular parameters which have the strongest relationship with cycling economy. This study tests the hypothesis that 3D Kinematic and electromyographic (EMG) parameters have the potential to significantly influence cycling economy.

2. Methods

Participants

Twenty-five male cyclists volunteered to take part in this study. Participants were active cyclists engaging in training at least three times per week. All were free from pathology at the time of data collection and written informed consent was provided in accordance with the declaration of Helsinki. The procedure was approved by the, School of Sport Tourism and Outdoors ethics committee, at the University of Central Lancashire. The age and body size characteristics of the participants were: age 31.27 ± 3.19 years, height 173.76 ± 4.11 cm and body mass 69.20 ± 5.19 kg.

Procedure

All data collection was completed using a cycle ergometer (Monark Ergomedic 874E, Monark Exercise, AB, Varberg, Sweden). Participants were required to cycle at a constant workload of 180 W, maintaining a cadence of 80 rev/min throughout. Saddle height was determined using the LeMond (1987) formula.

Kinematic data were obtained using an eight camera optoelectric motion capture system (Qualisys Medical AB, Goteburg, Sweden) using a capture frequency of 250 Hz. The calibrated anatomical systems technique (Cappozzo et al. [3]) was used to quantify segmental kinematics. To delineate the anatomical frames of the foot, shank, thigh and torso, retroreflective markers were positioned onto the calcaneus, 1st and 5th metatarsal heads, medial and lateral malleoli, medial and lateral epicondyle of the femur, greater trochanter and iliac crests, acromion process, xiphoid process and C7. To define the pelvic coordinate axes, additional markers were placed on the anterior (ASIS) and posterior (PSIS) superior iliac spines. Tracking clusters were also positioned on the shank and thigh segments. A static calibration trial was conducted during which the participant stood in the anatomical position in order for the positions of the anatomical markers to be referenced in relation to the tracking clusters. The hip joint centre was defined using regression modelling based on the position of the ASIS markers (Sinclair et al. [20]).

Surface EMG activity was obtained using a sampling frequency of 1000 Hz from the Rectus Femoris (RF), Tibialis Anterior (TA), Gastrocnemius (GM), Erector spinae (ES) and Biceps Femoris (BF) muscles using bipolar electrodes, with an interelectrode distance of 19 mm, connected to an interface unit (Biometrics LTD, SX230FW). To minimize cross-talk interference from nearby muscles, the electrodes were placed on the bellies on the appropriate muscles in alignment with the muscle pennation with respect to the recommendations of SENIAM (Hermens, Freriks, Disselhorst-Klug and Rau [12]). Prior to electrode placement, the skin was shaved, abraded then cleaned using an ethanol swab to minimize skin impedance, and support proper recordings of the muscle electrical potentials.

Breath-by-breath measurements of expired gases were made using a MetaLyser II (Cortex Biophysic, Leipzig, Germany). The test-retest reliability of the Metalyzer system has been demonstrated by Sinclair et al. [21] to be very good for steady state aerobic protocols (R^2 = 0.95). In addition, pilot testing also confirmed post protocol blood lactate concentrations to be < 2.0 mmol/L, indicating a negligible anaerobic contribution. Before each testing session the system was calibrated by inputting the atmospheric pressure, following which the pneumotach volume sensor was also calibrated using a 3 L syringe (Hans Rudolph, Inc., Kansas city USA). The sensors were calibrated using ambient air and also known gas concentrations of 5.09% O_2 and 14.46% CO_2. As VO_2 can be affected by circadian rhythms data was collected between the hours of 1400 and 1500 for all participants. The testing protocol itself consisted of steady-state cycling protocol's at the determined workload of 6 min duration in accordance with the Sinclair et al. [21] technique for aerobic protocols. All participants reported to the laboratory a minimum of 4 hours postprandial. Water was consumed ad libitum, pre and post-test.

Data processing

Kinematic curves were time normalized to 100% of the pedal cycle. Movement trials were digitized using Qualisys Track Manager then exported as C3D files. Kinematic parameters were quantified using Visual 3-D (C-Motion, Germantown, USA) after marker data were smoothed using a low-pass (Butterworth 4th order zero-lag) filter at a cut off frequency of 15 Hz (Winter 1990). Discrete parameters of (1) peak angle during the pedal cycle and (2) relative range of motion (ROM) from top dead centre-peak angle, (3) peak angular velocity, were extracted for inclusion into the analysis.

EMG signals from each of the five muscles were full wave rectified and then filtered using a Butterworth zero lag low-pass 4th order filter with a cut-off frequency of 10 Hz, to create a linear envelope. EMG data from each muscle were normalised to an isometric maximum voluntary contraction (MVC) which was obtained from each participant for each muscle. Isometric muscle actions were obtained using a Cybex NORM isokinetic dynamometer in accordance with the protocol outlined by Burden et al., (2003). EMG measures extracted from were; mean and peak normalized (% MVC) amplitude during the pedal cycle for each muscle.

Statistical analyses

A factor analysis was used to select a smaller number of variables to be included in the regression analysis. These factors were then entered into the multiple regression analysis which was conducted with VO_2 as criterion and the 3D kinematic and EMG parameters as independent variables. The significance level for the regression model was set at the $p \leq 0.05$ level. The independent variables were examined for co-linearity prior to entry into the regression model using a Pearson's correlation coefficient matrix and those exhibiting high co-linearity $R \geq 0.7$ were removed. All statistical procedures were conducted using SPSS 21.0 (SPSS Inc, Chicago, USA).

3. Results

VO_2 and EMG measurements

The analysis revealed mean ± standard deviation VO_2 measurements of 36.25 ± 5.64 ml.kg.min^{-1}. Table 1 and Fig. 4. present the EMG parameters obtained during this study.

Three-dimensional kinematics

Figures 1–3 present the 3D kinematic waveforms and obtained during this study.

Regression analysis

The regression model was found to be significant Adjusted $R^2 = 0.747$, $p < 0.01$. Two parameters were determined by the regression model as significant predictors of VO_2; peak sagittal plane knee extension velocity (Adj $R^2 = 0.624$, $p < 0.01$, $t = 7.14$) and mean activation of the RF muscle (Adj $R^2 = 0.123$, $p < 0.01$, $t = 3.269$).

Discussion

The current study examined the biomechanical and neuromuscular parameters which have the strongest association with cycling economy. This represents the first study to examine the 3D kinematic and surface EMG parameters linked with economy during steady state cycling. This study has importance given the relationship between cycling economy and performance. For example, it has been demonstrated that for an elite cyclist with 70 kg mass, a 1% improvement in economy equates to a 48 s improvement in 40 km time trial time (Coyle et al. [5]).

In support of the primary hypothesis, our findings confirm that 3D kinematic and EMG parameters are able to predict VO_2 during steady state cycling. That peak knee extension velocity is strongly correlated with VO_2 is to be expected as extension of the knee, during the pedal cycle, has been linked strongly to the transfer of power to the pedals during cycling (Elmer et al. [8]). This is not surprising, given its role in the generation in the rotational power of the crank and subsequent relationship to energy expenditure during cycling. Furthermore, activation of the Rectus Femoris was found to be strongly associated with VO_2, supporting the observations of Martin and Morgan [16]. These researchers also noted that variables describing muscular effort have the greatest potential to determine metabolic energy demands during steady state exercise. The uni-articular quadriceps muscles contract concentrically to overcome the resistive torque and have been shown to contribute 34–39% of the mechanical energy required to rotate the crank during cycling (Raasch et al. [18]). This is considerably more than any other muscle group. Therefore, it is not surprising that the RF muscle, as the largest of the quadriceps group, contributes significantly to economy during cycling (Ericson et al. [9]).

The findings of this study may allow recommendations for specific training modifications to be made with the aim of improving cycling economy. It has been recognized that improvements in cycling economy can be mediated through alterations in training modality (Loveless et al. [14]). These studies have typically been associated with increased lower extremity strength. Sunde et al. [27] showed that strength training of the quadriceps through half-squat exercises improved cycling economy. Hansen et al. [11] similarly observed a 3% improvement in cycling economy following a strength training program. Finally, Loveless et al. [14] demonstrated a 12 % improvement in cycling economy in a group of non-trained cyclists following 8 weeks of maximal strength training.

Table 1. Mean and peak EMG amplitudes for each of the observed muscles

	RF		BF		ES		GM		TA	
	Peak	Mean	Peak	Mean	Peak	Mean	Peak	Mean	Peak	Mean
Mean (% MVC)	0.48	0.25	0.35	0.18	0.60	0.42	0.58	0.35	0.36	0.19
Standard deviation	0.15	0.11	0.19	0.18	0.29	0.22	0.27	0.29	0.13	0.17

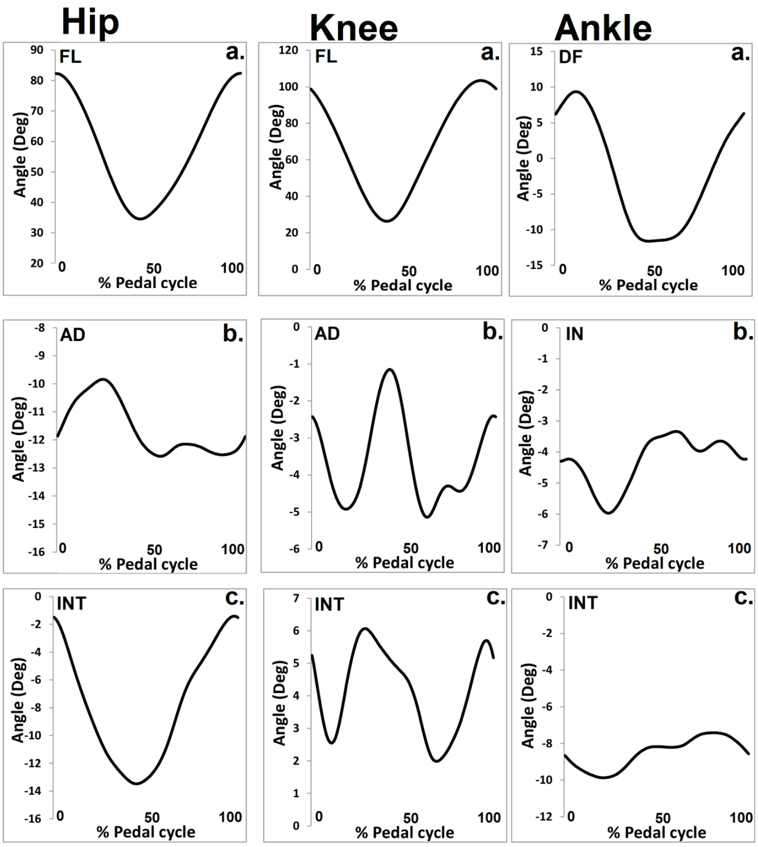

Fig. 1. Mean hip, knee and ankle angles in the (a) sagittal, (b) coronal, and (c) transverse planes (FL = flexion, DF = dorsiflexion, AD = adduction, IN = inversion, INT = internal)

These observations also provide support to the findings of the current investigation, that linked knee extension velocity and RF activation to cycling economy. As the principal contributor to knee extension, the quadriceps muscle is of critical importance to the generation of rotational crank movement. From a biomechanical perspective, strength training of the quadriceps muscle group may be of particular importance for cyclists who wish to improve their performance. However, increases in economy, via increases in maximal potential force production, may necessitate the recruitment of fewer motor units in this muscle group to produce the same output, thus improving economy.

Although the regression model in the current investigation was statistically significant, the model suggests that variance in VO_2 that was not accounted for by the 3D kinematic and EMG parameters that were entered into the model. Some of the remaining variance may be attributable to the composition of type I and II muscle fibres present in these cyclists, which was not considered in the current investigation. In addition, endurance performance in cycling has been shown to be strongly correlated with strength capacity (Sunde et al. 2010). Lower body maximal strength has been proposed to accelerate the rate of fatigue in type I muscle fibres, necessitating recruitment of metabolically less efficient type II muscle fibres (Crow and Kushmerick [7]). This would result in a lower efficiency and thus increased O_2 cost of cycling. Therefore, future analyses using regression based modelling techniques, to determine the biomechanical factors that contribute to energy expenditure during steady state cycling, may wish to consider indices of lower extremity strength.

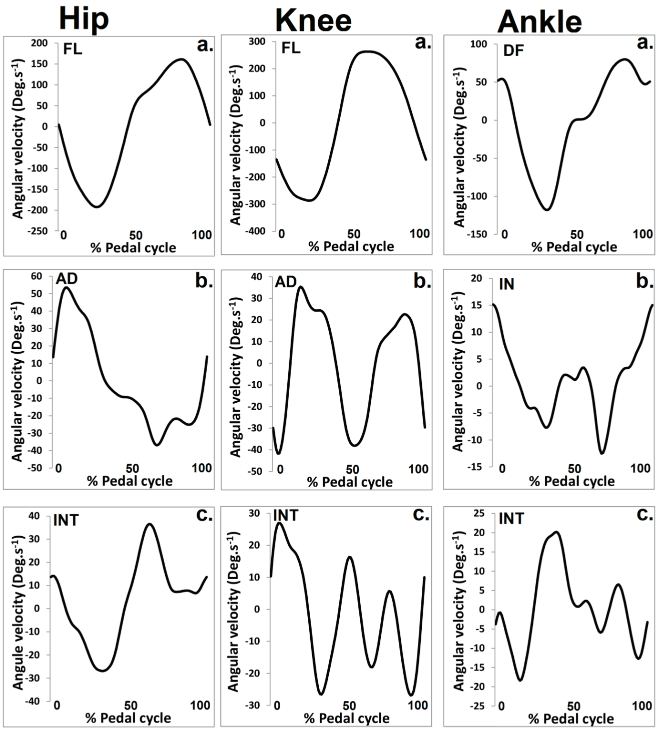

Fig. 2. Mean hip, knee and ankle angular velocities in the (a) sagittal, (b) coronal, and (c) transverse planes (FL = flexion, DF = dorsiflexion, AD = adduction, IN = inversion, INT = internal)

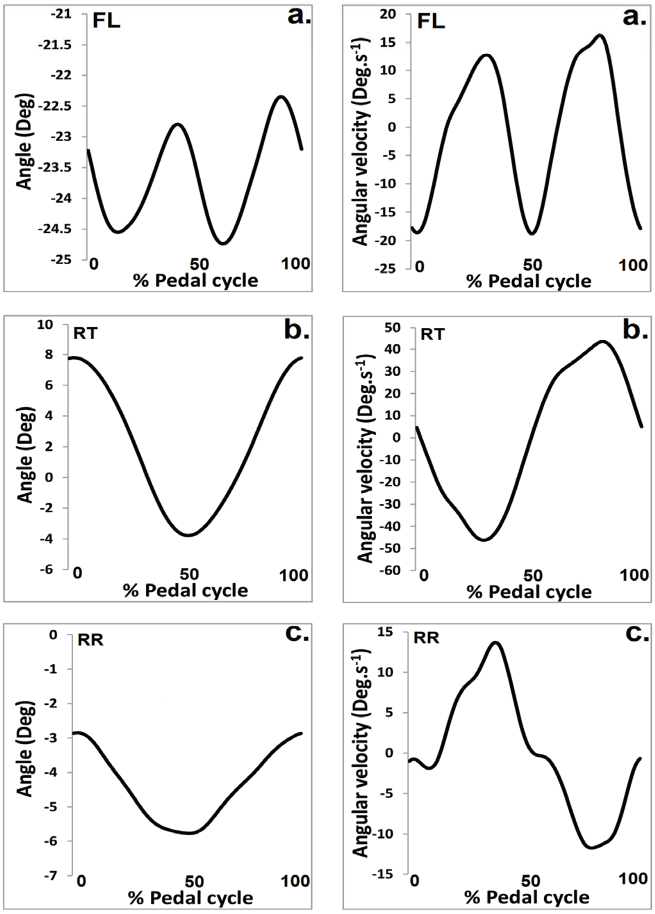

Fig. 3. Mean torso angles and angular velocities in the (a) sagittal, (b) coronal, and (c) transverse planes (FL = flexion, RT = right tile, RR = right rotation)

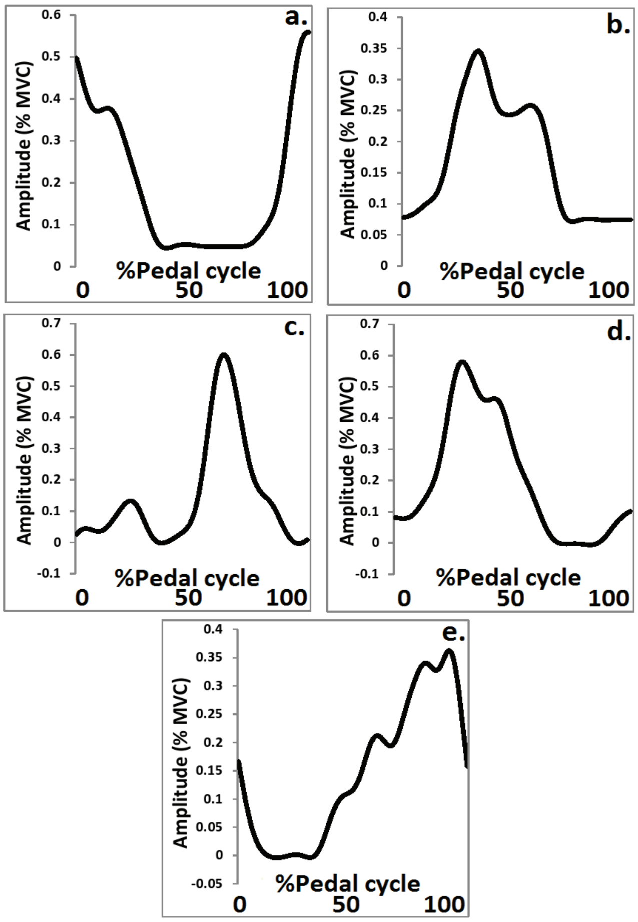

Fig. 4. EMG amplitudes obtained from each muscle (a = RF, b = BF, c = ES, d = GM, e = TA)

5. Limitations

Although steady state VO_2 can be measured very reliably (Sinclair et al. [21]), it is not possible to determine what proportion of the total energy expenditure contributes to actual mechanical work needed to turn the pedals as opposed to the energy expended for other bodily processes. Whilst we attempted to reduce the variability in VO_2 measurements by examining only experienced cyclists, and examining only steady-state exercise at intensities below that of the aerobic threshold, this remains a potential source of variability that cannot be fully controlled.

Also, this study utilized a pre-set workload which was selected based on the participants own abilities, and was maintained using a set cadence of 80 rpm. The energetically optimal cadence is likely to be highly individual and found at a muscle shortening velocity that is close to maximal power and efficiency in isolated muscle (Barclay et al. [1]). Some studies have reported that the lowest cadence's are most effective (Chavarren and Calbet [4]; Lucia et al. [15]; Samozino et al. [19]; Widrick et al. 1992), whilst some claim that the highest pedalling rates are most effective (Foss and Hallen [23]). It may have been more appropriate to allow the cyclists to select their own pedal cadence that that would produce the required power output.

That the current investigation utilized only trained cyclists may serve to limit the generalizability of this investigation. Trained cyclists are likely to adopt different pedalling mechanics when compared to recreational and elite cyclists, thus the factors that contribute to the energy required to maintain their race pace may differ. However, it should be noted that Moseley et al. [17] found no difference in cycling efficiency between world class and recreational cyclists. This is an interesting notion, as majority of the literature reports that cycling experience does not appear to influence efficiency. This certainly requires additional attention in future work to determine whether cyclists of different abilities have different correlates of energy expenditure.

Finally, that this study used a laboratory based protocol is also a limitation as the ecological validity of the findings are compromised. Whilst laboratory based cycling analyses do have the advantage of being more rigidly controlled compared to studies conducted in the field; consideration must be given for the results to be best applied to its target population and environment. This is particularly evident in measurements of respiratory gases. Jones and Doust [13] reported treadmill running to be metabolically lower then outdoor running at the same velocity and incline. Furthermore, whilst turbo trainers and cycle ergometers provide accurate measurements of torque, cadence and power negate several elements that are required during road cycling outdoors, namely balance and the additional work required to overcome mechanical and biological drag during movement. It is recommended that future analyses should replicate the current investigation using an ecologically valid protocol movement in order to determine whether alternative biomechanical parameters may contribute to the energy required to maintain a set workload.

6. Conclusion

In conclusion, this study provides new information regarding the 3D kinematic and sEMG parameters associated with the economy during cycling. The current investigation documents that knee extension angular velocity and activation of the RF muscle are the most pertinent to steady state economy during cycling. That a significant proportion of the variance in VO_2 was explained by a small number of biomechanical parameters, which suggests that these parameters are clearly pertinent to cycling economy. It is therefore conceivable that cyclists may benefit from exposure to training techniques geared towards the modification of their pedalling mechanics specific to this study. Whilst the outcomes of previous analyses featuring biomechanical feedback to reduce energy expenditure have generally not been positive, future work should still focus on implementing interventions to improve cycling economy.

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