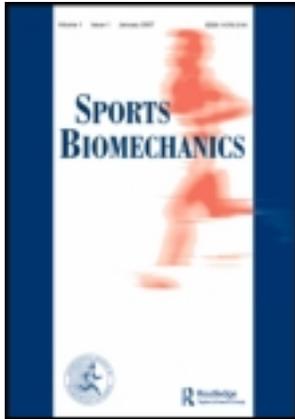


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## Neuromuscular control and running economy is preserved in elite international triathletes after cycling

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### Abstract

Running is the most important discipline for Olympic triathlon success. However, cycling impairs running muscle recruitment and performance in some highly trained triathletes; though it is not known if this occurs in elite international triathletes. The purpose of this study was to investigate the effect of cycling in two different protocols on running economy and neuromuscular control in elite international triathletes. Muscle recruitment and sagittal plane joint angles of the left lower extremity and running economy were compared between control (no preceding cycle) and transition (preceded by cycling) runs for two different cycle protocols (20-minute low-intensity and 50-minute high-intensity cycles) in seven elite international triathletes. Muscle recruitment and joint angles were not different between control and transition runs for either cycle protocols. Running economy was also not different between control and transition runs for the low-intensity ( $62.4 \pm 4.5$  vs.  $62.1 \pm 4.0$  ml/min/kg,  $p > 0.05$ ) and high-intensity ( $63.4 \pm 3.5$  vs.  $63.3 \pm 4.3$  ml/min/kg,  $p > 0.05$ ) cycle protocols. The results of this study demonstrate that both low- and high-intensity cycles do not adversely influence neuromuscular control and running economy in elite international triathletes.

**Keywords:** EMG, kinematics, running economy, transition, triathlon

### Introduction

Triathlon is an unique sport because overall race performance is determined by the ability to excel at and link three separate disciplines (Millet & Vleck, 2000). Of the three disciplines, running is the most important for elite Olympic distance race success (1,500 m swim, 40 km cycle, 10 km run) (Vleck et al., 2006). However, running after cycling is very demanding and the ability to limit cycling-induced biomechanical and/or physiological alterations during running is of high importance in elite triathlon (Millet & Vleck, 2000).

Previous studies that have investigated the effect of cycling on subsequent running biomechanics have reported inconsistent and sometimes transient changes in muscle activity and kinematics that may be due to altered running speed (Hausswirth et al., 1997;

Gottschall & Palmer, 2002; Heiden & Burnett, 2003). Further, in one of those studies reporting changes in running muscle activation after cycling, data collection in the field precluded the acquisition of kinematic data. Therefore, it is possible that the changes in muscle activity may be explained by alterations in joint motion. A more recent study reported that running kinematics and muscle recruitment were altered in 46% of moderately trained triathletes after a 45-minute cycle (Bonacci et al., 2010). In that study, changes in the angle of the ankle at footstrike were significantly associated with the change in running economy after cycling. Triathletes typically experience a decrease in running economy when running after cycling compared to isolated running (Hauswirth et al., 1997; Hue et al., 1997). The decrement in running economy is variable and may be a reflection of ability, with higher-performing athletes displaying less impairment in running economy than their lesser-performing counterparts (Millet et al., 2000).

There is very little evidence for the effect of cycling on running neuromuscular control (i.e. control of muscle recruitment and kinematics) in elite triathletes. One study reported that lower limb joint angles were unchanged but muscle activity altered in 36% of highly trained triathletes when running after cycling (Chapman et al., 2008). The absence of kinematic changes in these athletes suggests that highly trained triathletes have less difficulty reproducing their pre cycling running kinematics than moderately trained triathletes. However, that study utilised a 20-minute low-intensity cycle protocol to investigate the direct effect of cycling on running neuromuscular control, irrespective of fatigue. While this protocol provides valuable insight, 20 minutes of cycling does not reflect normal triathlon training and competition conditions. Further, running economy was not measured in that study so the implications of altered muscle recruitment on running performance in elite triathletes are not yet known. Therefore, knowledge of the effect of cycling on running neuromuscular control and performance is still incomplete in elite triathletes. This knowledge may eventually have important practical implications in identifying and training triathletes at all levels.

The purpose of this study was to investigate (a) the effect of cycling on running neuromuscular control and economy in elite international triathletes; and (b) if the 20-minute low-intensity cycle protocol induces similar neuromuscular and performance alterations to that of a 50-minute high-intensity cycle. Given that elite triathletes are thought to display less mechanical and performance alterations after cycling than their lesser-trained counterparts (Millet et al., 2001; Millet & Bentley, 2004), it was hypothesised that both cycle protocols would have no effect on neuromuscular control and running economy in these athletes.

## **Methods**

### *Participants*

Strict inclusion criteria of recent major international competition were used to ensure only elite Olympic distance triathletes participated in the study. Seven triathletes (4 male, 3 female), aged  $24.9 \pm 3.7$  years participated. All triathletes had represented Australia at the international level and the group included four Olympians and a 2009/2010 World Champion. The triathletes had been competing in triathlon for  $9.6 \pm 4.2$  years and had swum  $23.2 \pm 3.7$  km, cycled  $317.8 \pm 51.5$  km and ran  $77.1 \pm 12.5$  km in  $4.7 \pm 0.8$ ,  $4.9 \pm 0.4$  and  $5.5 \pm 0.5$  training sessions per week, respectively. Participants provided written informed consent and procedures were approved by Institutional Human Research Ethics.

*Electromyography*

Electromyographic (EMG) recordings were made from the tibialis anterior, gastrocnemius lateralis, soleus, vastus medialis, vastus lateralis, biceps femoris and semitendinosus muscles of the left leg. Muscle recordings were performed using bipolar Ag/AgCl surface electrodes with circular pre-gelled contact areas of 10 mm and a fixed interelectrode distance of 20 mm (Nicolet Biomedical Fitchburg, Winconsin, United States). Skin preparation procedures and electrode locations were in accordance with established procedures; with reference to published recommendations for optimal signal quality and innervations zone location (Rainoldi et al., 2004; Chapman et al., 2009). A ground electrode (3M Health Care, St Paul, Minnesota, United States) was positioned over the medial tibial shaft. EMG data were recorded with a Noraxon Myosystem 1400A (Noraxon Scottsdale, Arizona, United States), sampled at 3,000 Hz, band-pass filtered between 10 and 500 Hz and digitised by a 16-bit analog-to-digital convertor (VICON MX: Oxford Metrics Ltd, Oxford, UK). EMG cables were fixed using Fixomull® (BSN Medical, Hamburg, Germany) extensible dressing and Surgifix® (BSN Medical, Victoria, Australia) elastic bandage and electrodes were not moved or replaced between control and transition runs to maximise reproducibility.

*Joint angles*

Sagittal plane motion of the left lower limb was measured using a 17 camera VICON MX motion analysis system (Oxford Metrics Ltd, Oxford, UK). Coordinates of 14 mm retroreflective markers were sampled at 250 Hz and joint angle data calculated using the Plug in Gait® lower body model, which has been described and validated previously (Growth et al., 1997). Markers were secured using double-sided tape and Fixomull® (BSN Medical, Hamburg, Germany) extensible dressing and remained unchanged between control and transition runs to maximise reproducibility.

*Physiological measurements*

Running economy was determined by measuring the submaximal  $\text{VO}_2$  during the final minute of a 5-minute constant velocity run as described in detail previously (Saunders et al., 2004). Five minutes was deemed an adequate time to reach steady state based upon previous research (Saunders et al., 2004). Heart rate (HR), blood lactate concentration and rating of perceived exertion (RPE) were collected during the final minute of the cycle. RPE were obtained using a Borg 15-point (6-20) scale, HR was measured by short-range telemetry (Polar Vantage NV, Kempele, Finland) and a capillary blood sample was drawn for the measurement of blood lactate (mmol/l).

*Procedure*

Neuromuscular control (lower limb joint angles and EMG) and running economy were compared between control (no preceding cycle) and transition (preceded by cycling) runs in elite triathletes under two conditions: (i) a 20-minute low-intensity and (ii) a 50-minute high-intensity cycle. The order of the bike conditions was randomised and separated by 48 hours.

After a standardised 5-minute warm up, triathletes performed a 5-minute control (or baseline) run, and after 10 minutes of recovery, a cycle (low-intensity or high-intensity), followed immediately by a 5-minute transition run (i.e. run off-the-bike). To standardise the transition period between bike and run, yet replicate the demands of competition

a controlled period of 60 seconds was allowed to enable triathletes to dismount the ergometer and change footwear. Running speed remained constant for the 5-minute control run and was the same for the transition run (18 km/hr for males and 16 km/hr for females) to enable a direct comparison of neuromuscular control and running economy pre and post cycling. These speeds were chosen as they closely resemble that sustained during elite triathlon competition (Vleck et al., 2008; Le Meur et al., 2009). All triathletes had considerable experience of running on a treadmill and pacing their running. Running trials were performed on a custom-built treadmill with no incline (Australian Institute of Sport, Belconnen, Australia). EMG, kinematic and  $\text{VO}_2$  data were collected each minute throughout the running trials.

Cycling trials were performed on a custom-built wind-braked ergometer (Australian Institute of Sport, Canberra, Australia) fitted with the triathletes' own pedal system. The seat height and handlebar position in relation to crank centre on the ergometer were matched to each triathlete's riding position. The low-intensity condition was 20 minutes in duration and replicated an established protocol that has been shown not to induce neuromuscular fatigue in highly trained triathletes (Chapman et al., 2009). Triathletes cycled at their preferred cadence for the first 5 and final 3 minutes of the cycle period. Four conditions of individual preferred cadence, 55-60, 75-80 and 95-100 rev/min were randomly ordered in 3-minute durations from the 6th to 17th minute of the cycle period to simulate the varying cadences of normal cycling. The high-intensity cycle replicated an established power profile test that is 50 minutes in duration and involves maximal power outputs for durations typically encountered during road race conditions (Quod et al., 2010). A 3-minute warm up consisted of cycling between 100 and 250 W. The cycle protocol involved seven maximal efforts of 6, 6, 15, 30, 60, 240 and 600 seconds duration interspersed with active recovery periods of 54, 174, 225, 330, 480 and 600 seconds, respectively. The first two 6-second efforts were completed from a stationary start in a standing position, whereas the remaining efforts were completed from a rolling effort. Triathletes were instructed to produce as much power as possible in the efforts and cycle at a comfortable intensity during the recovery periods (typically  $\sim 100$  W).

#### *Data management*

Data management replicated established procedures (Chapman et al., 2009). EMG data were adjusted for DC-offset, full-wave rectified and bandpass filtered between 10 and 500 Hz. Joint angle data were filtered with an automated generalised cross-validatory spline (Woltring, 1986) and sagittal plane joint angles calculated using the Plug-in-Gait<sup>®</sup> lower body model. Only sagittal plane joint angles were analysed as the major arcs of motion during running occur in this plane and kinematic data derived from skin-based markers display less reliability and validity in other planes of motion (Ferrari et al., 2008; Leardini et al., 2005). Individual strides of running were defined from foot contact to ipsilateral foot contact; identified using the trajectory of markers placed on the ankle and shoes, as validated previously (Zeni et al., 2008). EMG and joint angle data were time normalised to 101 data points to describe the gait cycle. Ten consecutive strides of data for each minute were selected and the average across those 10 strides was used for analyses. EMG data were amplitude normalised to the maximum measured EMG amplitude during the baseline run (% MAX) as per previous procedures (Chapman et al., 2009). Running economy was normalised to body mass (ml/min/kg).

Several established indices were derived from the EMG and kinematic data: (i) the EMG and joint angle waveforms or the "recruitment and movement patterns"; (ii) the average

EMG amplitude for a complete stride of running; (iii) the peak EMG amplitude; (iv) stride duration; (v) stride frequency and (vi) sagittal plane joint angle at foot contact; (vii) the maxima and minima joint angles and (viii) the total excursion of joint motion at the ankle, knee and hip.

### Data analysis

Data analysis procedures were based on previous findings (Chapman et al., 2009; Bonacci et al., 2010). Descriptive statistics including means and standard deviations were calculated for all variables. Independent variables were the low-intensity and high-intensity cycles. Dependent variables were running economy and neuromuscular control (EMG and joint angle variables).

Prior to comparisons of control and transition run data, the reproducibility of control run EMG and joint angle data was evaluated for each triathlete to ensure the baseline data was stable. Between-minute reproducibility was calculated using the coefficient of multiple correlation (CMC) and root mean square error (RMSE) between data from the average stride of the 3rd, 4th and 5th minute of the control run. Stride-to-stride reproducibility was calculated using the CMC and RMSE between the 10 strides of the 5th minute of the control run.

To determine changes in neuromuscular control between control and transition runs, EMG and joint angle waveforms of the 1st through to 5th minute of the transition run were plotted and compared to the 95% confidence interval of the control run. Discrete EMG and joint angle data from the 5th minute of the control run were compared with data from the 1st through 5th minute of the transition run using repeated-measures ANOVA. Significance level was set 0.05. Group main effects were further analysed with Bonferroni adjusted pairwise comparison of within-subject differences among time intervals. Running economy was compared between control and transition runs using a paired *t*-test. Assumptions of parametric tests were evaluated prior to analyses being performed and in the event of any violations, adjusted critical *F*-values and non-parametric tests would be utilised.

In addition to statistical significance, changes in running economy greater than 2.4% were interpreted as clinically meaningful in accordance with the smallest worthwhile change recommended by Saunders et al. (2004). All comparisons were performed for both cycle protocols.

The effect of cycling on running muscle recruitment and joint angle waveforms was also evaluated for individual triathletes. The transition run was defined as different to that of the control run when (i) the mean difference between control (5th minute) and transition run *x*th minute ( $x = 1-5$ ) waveforms exceeded  $2^\circ$  (joint angles) or 10% EMG amplitude and (ii) the 95% confidence interval for EMG or joint angle waveforms of the 5th minute and transition run *x*th minute were not overlapping for  $\geq 10\%$  of the stride. This criteria followed established procedures and the known typical error of our measurements as described previously (Chapman et al., 2009; Bonacci et al., 2010).

To investigate possible reasons for differences in neuromuscular control during the cycle-run transition between the low-intensity and high-intensity conditions; lactate, heart rate and RPE at the end of the cycling bout were compared using a paired sample *t*-test.

## Results

Control run EMG and joint angle waveform data were highly reproducible. CMC and RMSE for EMG data of the 3rd, 4th and 5th minute of the control run averaged  $0.97 \pm 0.1$

Table I. Physiological measures and running economy data ( $M \pm SD$ ).

	Low-intensity cycle protocol	High-intensity cycle protocol
Heart rate (b/min)	110.7 $\pm$ 4.8	165.9 $\pm$ 7.4*
Blood lactate (mM)	1.8 $\pm$ 0.8	10.9 $\pm$ 3.1*
Rating of perceived exertion	10.9 $\pm$ 1.5	16.6 $\pm$ 3.9*
Running economy (ml/min/kg)		
Control run	62.4 $\pm$ 4.5	63.4 $\pm$ 3.5
Transition run	62.1 $\pm$ 4.0	63.3 $\pm$ 4.3
%Change	- 0.4 $\pm$ 2.2%	- 0.1 $\pm$ 2.4%

\*Significantly different from the low-intensity cycle ( $p < 0.05$ ).

Note: *Physiological measures were obtained from the last minute of the cycling bout.*

and  $4.2 \pm 0.5\%$ , respectively on the low-intensity protocol day. It was  $0.97 \pm 0.1$  and  $3.7 \pm 0.7\%$  respectively on the high-intensity protocol day. CMC and RMSE for joint angle waveform data averaged  $0.99 \pm 0.1$  and  $0.6 \pm 0.4^\circ$ , respectively on the low-intensity protocol day; it was  $0.99 \pm 0.1$  and  $0.4 \pm 0.2^\circ$ , respectively on the high-intensity protocol day. CMC for stride-to-stride reproducibility of joint angle and EMG waveform data exceeded 0.95 for all triathletes on both days. RMSE for stride-to-stride reproducibility of joint angle and EMG data were less than  $1.9^\circ$  and  $5.1\%$ , respectively for all triathletes on both days.

As expected the high-intensity cycle was considerably harder work than the low-intensity cycle. HR, lactate and RPE were all significantly higher at the end of the high-intensity cycle compared to the low-intensity cycle (Table I). However, **running economy during the transition run was not different from the control run for either cycle protocols** (Table I). Group data of left lower limb EMG and sagittal plane joint angles were also not different between control and transition runs at any time point for either of the two cycle protocols (Figures 1 and 2; Tables II and III).

Only one triathlete demonstrated altered muscle recruitment during running after cycling. This triathlete demonstrated a decrease in amplitude of biceps femoris EMG that occurred immediately after the low-intensity cycle and persisted for the duration of the transition run (Figure 3). The altered muscle recruitment did not influence running economy and was not evident after the high-intensity cycle. Sagittal plane joint angles were unchanged for all triathletes.

## Discussion and implications

The ability to run at maximum efficiency after cycling is of the highest importance in elite triathlon (Millet and Vleck, 2000). Running efficiently requires a high level of neuromuscular control that is not adversely affected by the previous cycling. We found that cycling does not adversely influence running economy and neuromuscular control of the left lower limb in elite international triathletes. Sagittal plane joint angles were preserved for all triathletes after both the low-intensity and high-intensity cycle protocols and muscle recruitment was altered in only one of seven (14%) triathletes after the low-intensity cycle. The training and medical history of this one triathlete did not differ from the remaining triathletes. No triathlete demonstrated altered muscle recruitment after the high-intensity cycle.

Our finding that neuromuscular control is preserved during running after cycling is consistent with previous reports investigating mechanical alterations during running after cycling. With the exception of a more forward leaning posture, kinematics remain

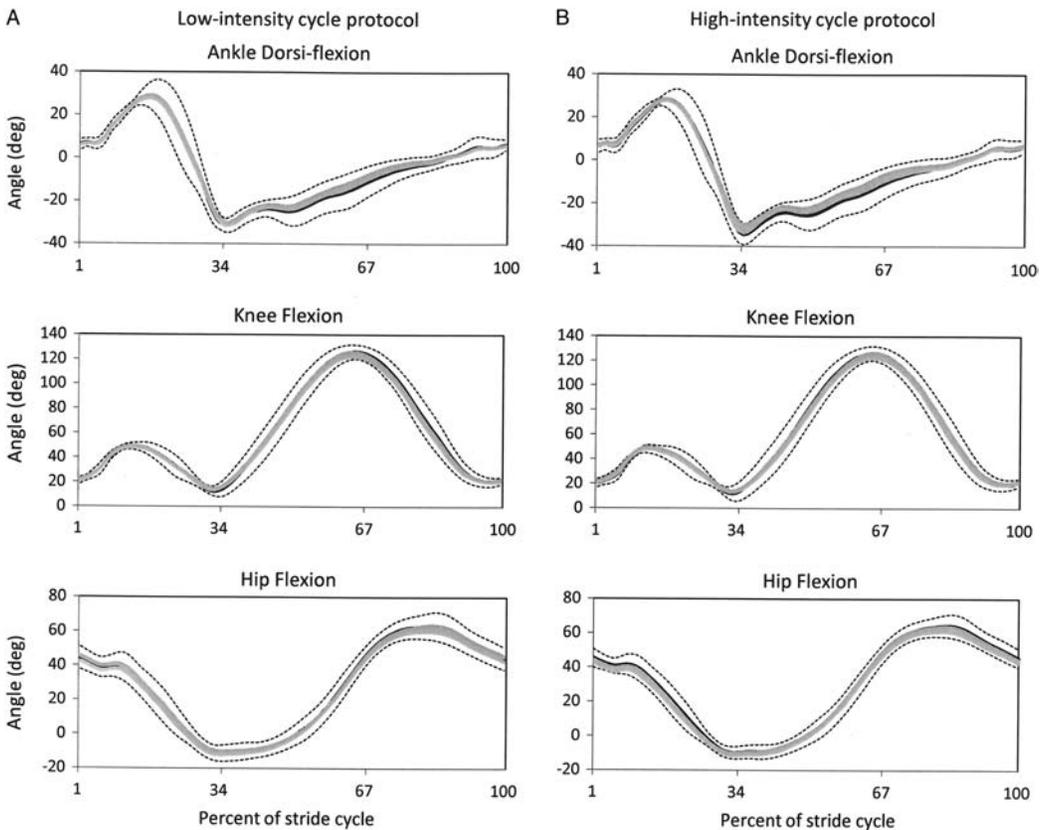


Figure 1. Sagittal plane joint angles of control run (mean, *solid black line*; 95% confidence interval, *dotted black lines*) and transition run minutes 1-5 (mean, *grey lines*) for the low-intensity cycle protocol (A) and high-intensity cycle protocol (B). Angular displacements are in degrees (*y*-axis) and plotted for one complete stride of running (*x*-axis).

unchanged in experienced triathletes during running after cycling (Quigley and Richards, 1996; Hausswirth et al., 1997; Hue et al., 1997). Our finding that cycling altered muscle recruitment in only one triathlete (14%) is in contrast to a recent study that reported muscle recruitment was altered after cycling in 36% of highly trained triathletes (Chapman et al., 2008). The higher performance level of the current triathletes may explain the difference, as more experienced triathletes have been shown to display less mechanical and performance decrements than their lesser-experienced counterparts (Millet et al., 2000; Millet et al., 2001). For example, Millet et al. (2000) reported that middle-level triathletes display a greater increase in the vertical displacement of the centre of mass during the braking phase than elite triathletes, suggesting a less efficient stiffness regulation after cycling. In a further study by the same group, middle-level triathletes were shown to exhibit higher vertical displacement, acceleration and deceleration of the centre of mass than elite triathletes during the first minutes of running after cycling (Millet et al., 2001).

We have also recently shown that 46% (7 of 15) of moderately trained triathletes demonstrate changes in both muscle recruitment and sagittal plane kinematics when running after a high-intensity cycle (Bonacci et al., 2010). Importantly, in that study, changes in joint angles were closely related to alterations in running economy. An earlier study that also reported changes in muscle recruitment after cycling, utilised state-level

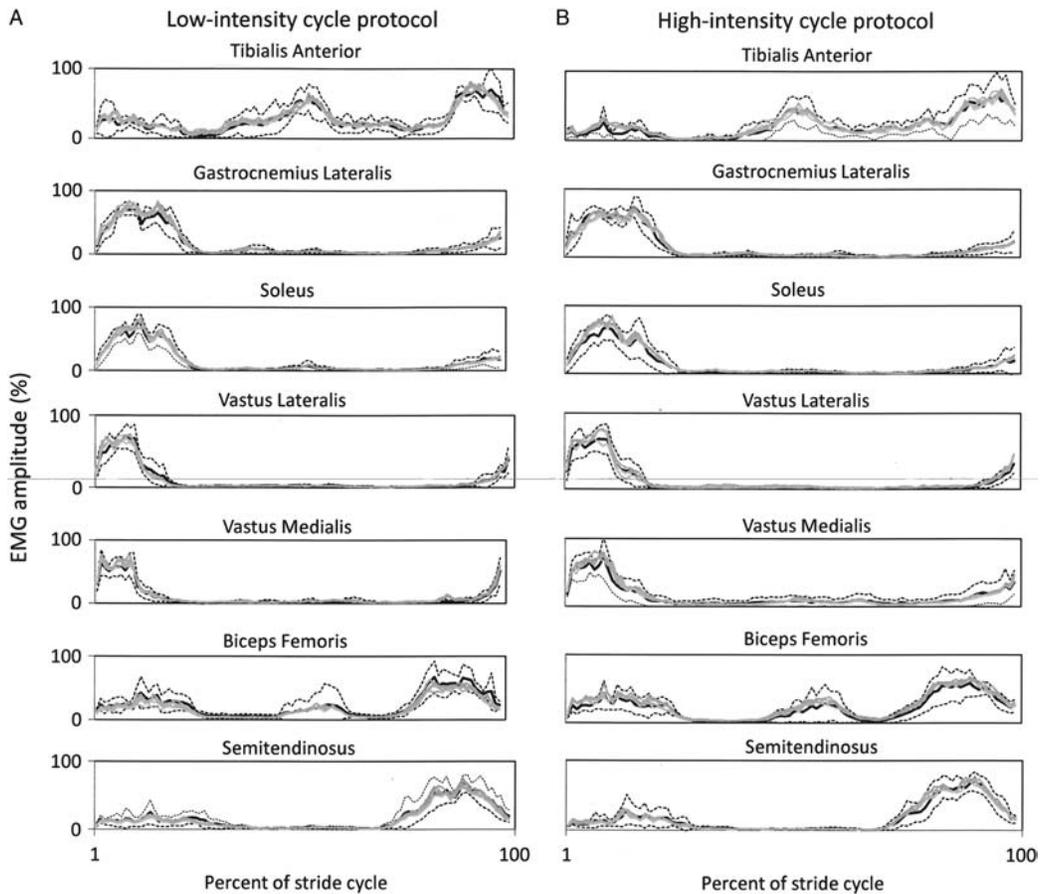


Figure 2. EMG data of control (mean, *solid black line*; 95% confidence interval, *dotted black lines*) and transition runs minutes 1–5 (mean, *grey lines*) for the low-intensity cycle protocol (A) and high-intensity cycle protocol (B). EMG data are presented as a percentage of MAX (*y*-axis) and percentage of the stride cycle (*x*-axis).

triathletes and running speed was not controlled, thus the changes may have been due to the lower calibre of athlete or altered running speed (Heiden & Burnett, 2003). The small sample size of the current study may also account for the smaller proportion of triathletes affected by cycling; however, there are only a small number of elite international triathletes and thus sample size was necessarily small to ensure sample homogeneity. While many factors contribute to triathlon race success, the ability of elite triathletes to maintain their movement and muscle recruitment patterns may be one part of why they are successful.

The finding that muscle recruitment was altered in one triathlete after the low-intensity cycle but not the high-intensity cycle was unexpected. It is reasonable to suppose that any alteration in muscle recruitment after a low-intensity cycle would be magnified under high-intensity conditions when neuromuscular fatigue is present. Reasons for this not occurring are unclear. It has previously been shown that a finding of altered muscle recruitment is repeatable using the same 20-minute cycle protocol (Chapman et al., 2009), but it may not be repeatable across various cycle protocols. The absence of changes in muscle recruitment after the high-intensity cycle may also be a training effect. Elite triathletes rarely run after a 20-minute submaximal cycle, therefore, this condition may be novel to them. There is

Table II. Joint angle data ( $^{\circ}$ ) of the control (C) and transition (T) runs ( $M \pm SD$ ).

	Low-intensity cycle (min)					High-intensity cycle (min)				
	C-5th	T-1st	T-3rd	T-5th	C-5th	T-1st	T-3rd	T-5th		
<b>Ankle</b>										
Footstrike	6.3 $\pm$ 3.3	5.8 $\pm$ 4.5	6.0 $\pm$ 4.3	5.5 $\pm$ 4.5	6.5 $\pm$ 4.1	6.6 $\pm$ 3.9	6.6 $\pm$ 3.8	6.7 $\pm$ 3.4		
Max.	31.4 $\pm$ 4.2	31.1 $\pm$ 5.1	30.9 $\pm$ 5.6	30.3 $\pm$ 5.8	30.3 $\pm$ 2.6	30.3 $\pm$ 2.4	30.2 $\pm$ 2.0	30.1 $\pm$ 2.3		
Min.	-33.6 $\pm$ 3.7	-34.0 $\pm$ 4.7	-34.7 $\pm$ 4.8	-33.4 $\pm$ 3.7	-36.7 $\pm$ 4.9	-35.8 $\pm$ 6.2	-36.8 $\pm$ 5.8	-36.4 $\pm$ 5.8		
Total excursion	63.4 $\pm$ 4.3	63.2 $\pm$ 5.5	63.5 $\pm$ 5.2	63.7 $\pm$ 5.6	67.0 $\pm$ 6.1	66.2 $\pm$ 7.0	67.0 $\pm$ 6.6	66.5 $\pm$ 6.6		
<b>Knee</b>										
Footstrike	20.3 $\pm$ 5.0	21.3 $\pm$ 4.6	21.3 $\pm$ 4.5	20.7 $\pm$ 4.4	21.1 $\pm$ 3.7	21.0 $\pm$ 3.6	21.4 $\pm$ 2.9	21.6 $\pm$ 2.9		
Max.	127.1 $\pm$ 7.8	126.0 $\pm$ 6.3	127.1 $\pm$ 6.3	125.6 $\pm$ 10.3	128.1 $\pm$ 7.8	127.5 $\pm$ 7.3	127.6 $\pm$ 7.4	126.1 $\pm$ 10.7		
Min.	8.1 $\pm$ 4.6	8.5 $\pm$ 4.6	9.0 $\pm$ 4.2	8.7 $\pm$ 4.6	9.3 $\pm$ 2.9	10.0 $\pm$ 2.7	10.2 $\pm$ 3.1	9.8 $\pm$ 3.3		
Total excursion	119.0 $\pm$ 8.0	117.5 $\pm$ 7.5	118.1 $\pm$ 6.4	117.2 $\pm$ 10.3	119.1 $\pm$ 8.1	117.5 $\pm$ 7.3	117.3 $\pm$ 7.4	116.3 $\pm$ 10.2		
<b>Hip</b>										
Footstrike	42.1 $\pm$ 7.1	42.9 $\pm$ 7.4	43.4 $\pm$ 7.8	42.3 $\pm$ 7.2	45.2 $\pm$ 7.3	43.8 $\pm$ 6.8	44.3 $\pm$ 7.0	44.5 $\pm$ 7.1		
Max.	62.4 $\pm$ 6.5	62.4 $\pm$ 5.9	63.0 $\pm$ 6.2	61.8 $\pm$ 7.7	65.8 $\pm$ 6.8	65.5 $\pm$ 7.4	65.5 $\pm$ 7.6	65.2 $\pm$ 8.8		
Min.	-12.8 $\pm$ 5.8	-12.4 $\pm$ 5.0	-12.3 $\pm$ 5.3	-12.3 $\pm$ 5.8	-10.6 $\pm$ 5.3	-10.4 $\pm$ 5.8	-10.9 $\pm$ 5.8	-10.5 $\pm$ 5.7		
Total excursion	75.3 $\pm$ 5.1	74.8 $\pm$ 3.8	75.3 $\pm$ 3.8	74.6 $\pm$ 7.3	76.4 $\pm$ 4.5	75.7 $\pm$ 3.8	76.3 $\pm$ 4.5	75.7 $\pm$ 7.2		

Note: Joint angle and EMG data were not different between the control and transition runs at any time point ( $p > 0.05$ ).

Table III. Average EMG amplitudes (%) of the control (C) and transition (T) runs ( $M \pm SD$ ).

	Low-intensity cycle (min)					High-intensity cycle (min)				
	C-5th	T-1st	T-3rd	T-5th		C-5th	T-1st	T-3rd	T-5th	
Tibialis anterior	26.4 ± 3.1	29.5 ± 4.9	28.1 ± 4.3	27.2 ± 4.8		23.3 ± 3.8	24.2 ± 3.1	22.2 ± 4.1	21.2 ± 2.7	
Gastrocnemius lateralis	15.9 ± 2.1	16.9 ± 3.2	17.1 ± 3.4	17.2 ± 3.1		15.3 ± 2.1	16.2 ± 4.0	15.0 ± 3.6	14.7 ± 3.4	
Soleus	14.0 ± 3.2	14.4 ± 1.8	14.4 ± 3.3	14.3 ± 3.4		13.5 ± 3.4	15.4 ± 4.4	14.9 ± 4.9	14.7 ± 4.8	
Vastus medialis	11.8 ± 1.8	12.1 ± 3.4	11.3 ± 2.9	11.0 ± 3.4		15.4 ± 7.0	15.1 ± 8.0	15.2 ± 8.4	15.6 ± 8.4	
Vastus lateralis	10.8 ± 1.8	11.1 ± 1.7	10.5 ± 1.2	10.6 ± 1.2		10.3 ± 2.7	10.5 ± 4.6	12.1 ± 2.6	12.9 ± 3.9	
Biceps femoris	22.6 ± 2.6	20.2 ± 7.5	19.4 ± 8.2	16.7 ± 7.2		23.3 ± 2.5	26.1 ± 2.7	25.3 ± 3.2	23.9 ± 3.7	
Semitendinosus	17.1 ± 5.6	17.0 ± 5.1	16.4 ± 4.7	16.4 ± 5.3		16.8 ± 1.5	18.0 ± 2.3	17.2 ± 3.2	16.3 ± 2.7	

Note: EMG amplitudes are presented as percentages of the maximum measured EMG amplitudes. EMG data were not different between the control and transition runs at any time point ( $p > 0.05$ ).

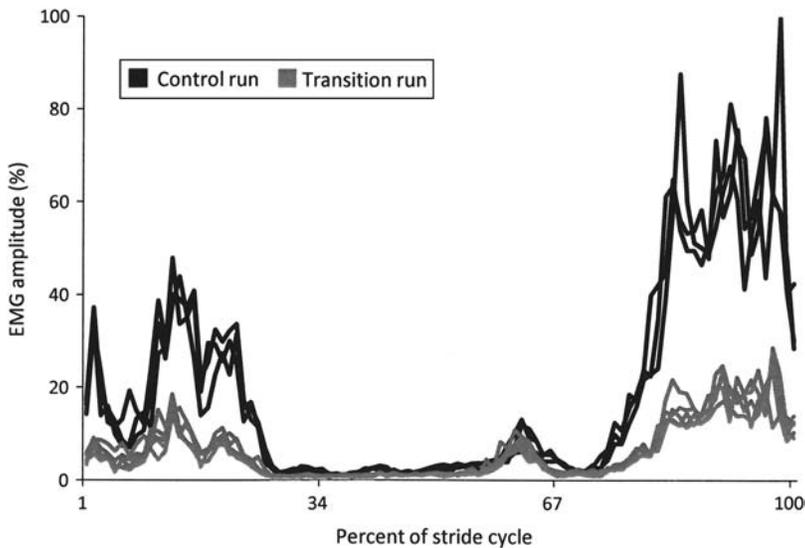


Figure 3. EMG data of the biceps femoris muscle from the one triathlete who demonstrated a change in muscle recruitment between control and transition runs. Data are from the 3rd, 4th and 5th minute of the control run (*black*) and minutes 1 through 5 of the transition run (*grey*). EMG data are plotted on the *y*-axis as a percentage of MAX and percentage of the stride cycle on the *x*-axis. The mean difference between control and transition runs was  $13.0 \pm 0.7\%$ .

evidence to suggest that when two novel tasks are performed in sequence, the central nervous system uses a generalised movement plan for both tasks but not specific for either (Karniel & Mussa-Ivaldi, 2002). That study showed that after-effects of the first task are seen during performance of subsequent task. The novelty of the 20-minute cycle condition may have caused some carryover of the pattern of cycling muscle recruitment to running, which is not seen during the more familiar race-like cycle conditions. Importantly, our data show that most elite triathletes are able to instantaneously reproduce their pre cycling running muscle recruitment and sagittal plane joint motion.

Running economy or the oxygen cost of running has previously been shown to be impaired during running after cycling when compared to running in isolation (Hauswirth et al., 1997; Hue et al., 1997). However, conflicting results have been reported and the extent of change appears related to experience level. For example, Millet et al. (2000) reported a 3.7% decrease in oxygen cost in elite international triathletes but a 2.3% increase in oxygen cost in regional-level triathletes after cycling. In another study by the same group both junior and senior male elite international triathletes showed no difference in oxygen cost after cycling, but junior female triathletes had a significantly greater increase in oxygen cost than senior female triathletes (Millet & Bentley, 2004). We found a negligible change in running economy after both the low-intensity and high-intensity cycles in elite international triathletes. Therefore, it appears that the physiological responses to cycling differ between elite international triathletes and their lesser experienced counterparts. Our results confirm that elite international triathletes have the ability to run at maximum efficiency despite previous cycling.

There are limitations of this study that need to be considered. The sample size was small, but necessarily so to ensure sample homogeneity. Only elite international triathletes were suitable for the study, of which there are relatively small numbers. Any increase in participant

numbers would have required the inclusion of lesser-trained athletes which would have compromised our criteria. Secondly, all running trials were performed on a treadmill under constant velocity conditions. While it is acknowledged that this does not reflect competition conditions, strict control of running velocity was required as kinematics and muscle recruitment can vary with running speed. More cautious interpretation of our results would be required if changes in speed were permitted. Extrapolation of treadmill running results to overground running may require some caution as differences in kinematics and muscle recruitment may exist (Wank et al., 1998; Baur et al., 2007). Finally, joint angles were measured only in the sagittal plane and it is possible that cycling-induced alterations in coronal and transverse plane running kinematics may have been overlooked. This may have important clinical implications and may require further investigation.

## Conclusion

The results of this study demonstrate that both a low-intensity and a high-intensity cycle do not adversely influence neuromuscular control and running economy in elite international triathletes. The ability to limit the negative effects of cycling is a unique feature of highly performing elite international triathletes and this may be one of many factors that contribute to the success of these athletes. It could be speculated that identifying triathletes who are able to preserve their neuromuscular control and running economy after cycling may distinguish those who could be successful in the sport.

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## References

- Baur, H., Hirschmuller, A., Muller, S., Gollhofer, A., & Mayer, F. (2007). Muscular activity in treadmill and overground running. *Isokinetics and Exercise Science*, *15*, 165–171.
- Bonacci, J., Green, D., Saunders, P. U., Blanch, P., Franettovich, M., Chapman, A. R. et al. (2010). Change in running kinematics after cycling are related to alterations in running economy in triathletes. *Journal of Science and Medicine in Sport*, *13*, 460–464.
- Chapman, A. R., Vicenzino, B., Blanch, P., Dowlan, S., & Hodges, P. W. (2008). Does cycling effect motor coordination of the leg during running in elite triathletes? *Journal of Science and Medicine in Sport*, *11*, 371–380.
- Chapman, A. R., Vicenzino, B., Hodges, P. W., Blanch, P., Hahn, A., & Milner, T. E. (2009). A protocol for measuring the direct effect of cycling on neuromuscular control of running in triathletes. *Journal of Sports Sciences*, *27*, 767–782.
- Ferrari, A., Benedetti, M. G., Pavan, E., Frigo, C., Bettinelli, D., Rabuffetti, M. et al. (2008). Quantitative comparison of five current protocols in gait analysis. *Gait and Posture*, *28*, 207–216.
- Gottschall, J. S., & Palmer, B. M. (2002). The acute effects of prior cycling cadence on running performance and kinematics. *Medicine and Science in Sports and Exercise*, *34*, 1518–1522.
- Growney, E., Meglan, D., Johnson, M., Cahalan, T., & An, K.-N. (1997). Repeated measures of adult normal walking using a video tracking system. *Gait and Posture*, *6*, 147–162.
- Hauswirth, C., Bigard, A. X., & Guezennec, C. Y. (1997). Relationships between running mechanics and energy cost of running at the end of a triathlon and a marathon. *International Journal of Sports Medicine*, *18*, 330–339.
- Heiden, T., & Burnett, A. (2003). The effect of cycling on muscle activation in the running leg of an Olympic distance triathlon. *Sports Biomechanics*, *2*, 35–49.

- Hue, O., Gallais, D. L., Chollet, D., Boussana, A., & Préfaut, C. (1997). The influence of prior cycling on biomechanical and cardiorespiratory response profiles during running in triathletes. *European Journal of Applied Physiology and Occupational Physiology*, 77, 98–105.
- Karniel, A., & Mussa-Ivaldi, F. (2002). Does the motor control system use multiple models and context switching to cope with a variable environment? *Experimental Brain Research*, 143, 520–524.
- Leardini, A., Chiari, L., Croce, U. D., & Cappozzo, A. (2005). Human movement analysis using stereophotogrammetry part 3. Soft tissue artifact assessment and compensation. *Gait and Posture*, 21, 212–225.
- Le Meur, Y., Hausswirth, C., Dorel, S., Bignet, F., Brisswalter, J., & Bernard, T. (2009). Influence of gender on pacing adopted by elite triathletes during a competition. *European Journal of Applied Physiology*, 106, 535–545.
- Millet, G. P., & Bentley, D. J. (2004). The physiological responses to running after cycling in elite junior and senior triathletes. *International Journal of Sports Medicine*, 25, 191–197.
- Millet, G. P., Millet, G. Y., & Candau, R. B. (2001). Duration and seriousness of running mechanics alterations after maximal cycling in triathletes: Influence of the performance level. *Journal of Sports Medicine and Physical Fitness*, 41, 147–153.
- Millet, G. P., Millet, G. Y., Hofmann, M. D., & Candau, R. B. (2000). Alterations in running economy and mechanics after maximal cycling in triathletes: Influence of performance level. *International Journal of Sports Medicine*, 21, 127–132.
- Millet, G. P., & Vleck, V. E. (2000). Physiological and biomechanical adaptations to the cycle to run transition in Olympic triathlon: Review and practical recommendations for training. *British Journal of Sports Medicine*, 34, 384–390.
- Quigley, E. J., & Richards, J. G. (1996). The effects of cycling on running mechanics. *Journal of Applied Biomechanics*, 12, 470–479.
- Quod, M. J., Martin, D. T., Martin, J. C., & Laursen, P. B. (2010). The power profile predicts road cycling mmp. *International Journal of Sports Medicine*, 31, 397–401.
- Rainoldi, A., Melchiorri, G., & Caruso, I. (2004). A method for positioning electrodes during surface EMG recordings in lower limb muscles. *Journal of Neuroscience Methods*, 134, 37–43.
- Saunders, P. U., Pyne, D. B., Telford, R. D., & Hawley, J. A. (2004). Reliability and variability of running economy in elite distance runners. *Medicine and Science in Sports & Exercise*, 36, 1972–1976.
- Vleck, V. E., Bentley, D. J., Millet, G. P., & Burgi, A. (2008). Pacing during an elite Olympic distance triathlon: Comparison between male and female competitors. *Journal of Science and Medicine in Sport*, 11, 424–432.
- Vleck, V. E., Bürgi, A., & Bentley, D. J. (2006). The consequences of swim, cycle, and run performance on overall result in elite Olympic distance triathlon. *International Journal of Sports Medicine*, 27, 43–48.
- Wank, V., Frick, U., & Schmidtbleicher, D. (1998). Kinematics and electromyography of lower limb muscles in overground and treadmill running. *International Journal of Sports Medicine*, 19, 455–461.
- Woltring, H. J. (1986). A FORTAN package for generalised cross-validated spline smoothing and differentiation. *Advances in Engineering Software*, 8, 104–113.
- Zeni, Jr, J. A., Richards, J. G., & Higginson, J. S. (2008). Two simple methods for determining gait events during treadmill and overground walking using kinematic data. *Gait and Posture*, 27, 710–714.