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ORIGINAL ARTICLE

Differences in joint power distribution in high and low lactate threshold cyclists

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Abstract

Purpose The biomechanical differences between cyclists with a high compared with a low blood lactate threshold (HLT; 80% VO_{2max} vs LLT, 70% VO_{2max}) have yet to be completely described. We hypothesize that HLT cyclists reduce the stress placed on the knee extensor muscles by increasing the relative contribution from the hip joint during high-intensity cycling.
Method Sixteen well-trained endurance athletes, with equally high VO_{2max} while cycling and running completed submaximal tests during incremental exercise to identify lactate threshold (LT_{VO_2}) while running and cycling. Subjects were separated into two groups based on % VO_{2max} at LT during cycling (high; HLT: 80.2 ± 2.1% VO_{2max}; $n = 8$) and (LLT: 70.3 ± 2.9% VO_{2max}; $n = 8$; $p < 0.01$). Absolute and relative joint specific powers were calculated from kinematic and pedal forces using inverse dynamics while cycling at intensities ranging from 60–90% VO_{2max} for between group comparisons.
Result There was no difference between HLT and LLT in LT_{VO_2} ($p > 0.05$) while running. While cycling in LLT, knee joint absolute power increased with work rate ($p < 0.05$); however, in HLT no changes in knee joint absolute power occurred with increased work rate ($p > 0.05$). The HLT generated significantly greater relative hip power compared with the LLT group at 90% VO_{2max} ($p < 0.05$).
Conclusion These data suggest that HLT cyclists exhibit a greater relative hip contribution to power output during cycling at 90% VO_{2max}. These observations support the theory that lactate production during cycling can be reduced by spreading the work rate between various muscle groups.

Keywords Lactate threshold · Cycling · Joint power

Abbreviations

HLT	High lactate threshold cyclist group
HR	Heart rate
LLT	Low lactate threshold cyclist group
LT	Lactate threshold
LT_{HR}	Heart rate at lactate threshold
LT_{VO_2}	Oxygen consumption at lactate threshold
RER	Respiratory exchange ratio
RPE	Rating of perceived exertion
VCO_2	Volume of expired carbon dioxide
VO_2	Volume of inspired oxygen
VO_{2max}	Maximal oxygen consumption

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Introduction

It has long been recognized that fatigue during exercise, and thus endurance performance ability, is related to muscle lactic acid production and that the degree of muscular metabolic stress can be assessed from lactate concentration in the blood (Costill 1970; Margaria et al. 1933). In cyclists with homogenous maximal oxygen consumptions (VO_{2max}) the primary predictor of endurance of performance is the blood lactate threshold (LT) (Coyle 1995; Coyle et al. 1988, 1991). The % VO_{2max} at LT can range from 60 to 85% in well-trained cyclists despite similarly high VO_{2max} values (Coyle et al. 1988). Part of the large differences in LT can be explained by differences in mitochondrial activity (Coyle et al. 1984; Joyner and Coyle 2008), but we have also reported that cyclists with similar mitochondrial activity can still display large differences in % VO_{2max} at LT (Coyle et al. 1988). This suggests that in addition to mitochondrial activity, other factor(s) might influence the degree of muscle stress and lactate concentration during exercise.

Previous work from our lab hypothesized that one of those additional factors determining % VO_{2max} at LT might involve the ability of the cyclist to spread the work of cycling to a large quantity of muscle mass and thus reduce the metabolic stress on the active fibers (Coyle 1995; Coyle et al. 1988). Based upon the muscle glycogen depletion patterns relative to total carbohydrate and blood glucose oxidation, high LT cyclists (81% VO_{2max}) appeared to recruited 22% more muscle mass than the low LT cyclists (66% VO_{2max}) while cycling at 80% VO_{2max} (Coyle 1995; Coyle et al. 1988). LT was also measured while running on a treadmill set to a 10% grade since it stresses many of the same muscles as cycling but elicits a recruitment pattern that is more natural in spreading the work to a large quantity of muscle (Bramble and Lieberman 2004). Cyclists with a low LT while cycling (66% VO_{2max}), yet high mitochondria activity, displayed a high LT (81% VO_{2max}) while running uphill suggesting that the low LT cyclists possess the ability to spread the work of exercise to a large quantity of muscle mass while running uphill, but not while cycling (Coyle 1995; Coyle et al. 1988). Furthermore, a 134% greater rate of muscle vastus lateralis glycogen depletion in low LT cyclists compared with the high LT cyclists suggested an over utilization of the knee extensors while cycling (Coyle et al. 1988).

Although physiological data suggest an over utilization of the knee extensor muscles in low LT cyclists, to date no study has compared the biomechanical difference (i.e. relative joint contribution to power) of high and low LT cyclists. Studies directly comparing relative joint contribution have done so in experienced and novice cyclists (Aasvold et al. 2019; Bini et al. 2014; Ohashi et al. 2007) and have found inconsistent results. Studies have found higher (Aasvold et al. 2019), lower (Ohashi et al. 2007), or no difference in relative hip contribution (Bini et al. 2014) between experienced and novice cyclists. Prior studies have made relative joint contribution comparisons at different absolute and relative work rates and/or relative exercise intensities. As both the absolute and relative joint powers of the lower extremity adjusts to increases in work rate (Ericson 1986; Skovereng et al. 2016a, b), comparing at different work rates (absolute or relative) makes interpretation and generalization somewhat tenuous (Aasvold et al. 2019; Bini et al. 2014; Ohashi et al. 2007). By comparing cyclists with similar VO_{2max} values but with different % VO_{2max} at LT while cycling, a direct comparison can be made at similar absolute and relative work rates (i.e.; % VO_{2max}).

Therefore, the objective of the present study was to compare high LT and low LT cyclists using specific joint power calculations to determine if high LT cyclists have higher relative contribution of the hip extensor muscles during high-intensity cycling (60–90% VO_{2max}; 175–360 W). We also hypothesized that compared with low LT cyclists, high LT cyclists might exhibit a lower relative knee power contribution during submaximal cycling.

Methods

Fifty-two well-trained endurance athletes were originally recruited. Thirty-six of those subjects did not obtain similar uphill running and cycling VO_{2max} values and were excluded ($VO_{2max} \leq 0.2$ L/min difference between running and cycling). The remaining 16 well-trained endurance athletes were separated into two groups: high % $LT_{VO_{2max}}$ (HLT, $n = 8$; $80.2 \pm 2.1\%$ VO_{2max}) and low % $LT_{VO_{2max}}$ (LLT, $n = 8$; $70.3 \pm 2.9\%$ VO_{2max}) while cycling. Having similar VO_{2max} values between cycling and uphill running served two purposes for our study. First, it assured the subjects were well-trained cyclists. If subjects had a lower VO_{2max} while cycling any differences in lactate threshold between groups could have simply been a result of their lack of cycling training. Second, equal VO_{2max} values between cycling and running allowed for lactate threshold testing during both modes to be compared at similar absolute and relative VO_{2max} values, therefore, allowing us to distinguish individuals that had low lactate thresholds solely while cycling.

A total of six testing visits were required. Visit 1 measured VO_{2max} while cycling and visit 2 measured VO_{2max} while running uphill. Visit 3 was used to determine LT_{VO_2} while cycling and Visit 4 determined LT_{VO_2} while running. Visits 5 and 6 measured joint-specific power during submaximal cycling. All subjects provided written informed consent in accordance with the University of Texas at Austin Institutional Review Board.

Maximal oxygen consumption while cycling and running

To assess VO_{2max} while running, subjects exercised for 8–12 min at constant velocity with increasing incline until fatigue as described previously (Costill and Winrow 1970). Each subject ran at a constant velocity while incline was increased by 2% every 2 min until exhaustion (5). For cycling tests, subjects exercised for 4 min at estimated 75% of VO_{2max} after which work rate increased by 10% every 2 min. After 10 min (estimated 105% stage of estimated VO_{2max}) if subjects did not yet reach fatigue, work rate was increased every minute thereafter by 3% until fatigue using an electromagnetically braked ergometer (Excaliber Sport, Lode, Groningen, The Netherlands). For both cycling and running, a successful VO_{2max} test was determine based on

ACSM criteria: RER > 1.1, maximal heart rate ± 10 bpm of predicted max heart rate (HR_{max}), plateau of ≤ 150 mL/min VO_2, and a rating of perceived exertion (RPE) > 17. Heart rate was measured continuously by a monitor worn around the chest (Suunto, Vantaa, Finland).

Respiratory analyses were determined using oxygen and carbon dioxide analyzers (Applied Electrochemistry, Models S-3A/I and CD-3A, respectively) while the participants breathed through a one-way valve (Hans Rudolph, Kansas City, MO, USA). Ventilation was measured via an inspiratory pneumotachometer (Hans Rudolph, Kansas City, MO, USA). VO_2, VCO_2, and RER were continuously monitored throughout the exercise test. The highest 30 s average of VO_2 was used as the measurement of VO_{2max}.

Lactate threshold testing

This protocol required 30 min of continuous exercise at submaximal intensities (5 min at each stage of approximately 40, 50, 60, 70, 80, 90% of VO_{2max}). During the cycling test, cadence was maintained at 80–100 RPM. During treadmill testing subjects ran at a constant 10% grade and speed was increased. A catheter (BD Instye™ Autoguard™ BC Shield IV, BD, Sandy, UT, USA) was inserted into an antecubital vein of the arm and flushed regularly with saline solution to remain patent (BD PosiFlush, BD, Sandy, UT, USA). Lactate threshold was determined from a series of venous blood samples obtained between minutes 4 and 5 in each stage. Blood samples were immediately deproteinized in 10% perchloric acid and were measured on the supernatant using enzymatic analysis. (Coyle et al. 1988, 1991; Farrell et al. 1979). The lactate threshold was defined as the exercise intensity that elicits a 1-mM increase above baseline in blood lactate concentration (Coyle et al. 1983). VO_2, VCO_2, RER, and HR (Suunto, Vantaa, Finland) were continuously monitored throughout the exercise test and were averaged over the final 4 and 5 min of each stage and during this time subjects also reported their RPE.

Joint specific powers

Subjects cycled on a laboratory ergometer (Velotron DynaFit Pro; RacerMate, Seattle, WA, USA) while wearing 3 M reflective markers at nine sites (acromion process, mid-axillary, greater trochanter, mid-femur, lateral epicondyle of the knee, mid-shank, lateral malleolus, the toe of the shoe, and heel of the shoe). Marker position in 3-dimensional space was determined through infrared motion capture (Vicon Motion Systems Ltd., Lake Forest, CA, USA). Normal and tangential components of force applied to the pedal were collected using a custom-designed force pedal with two piezo electric force transducers (Kistler, model 9251AQ01) at a sampling rate of 1200 Hz. Pedal forces were filtered by a third-order low-pass Butterworth filter with a cutoff frequency of 10 Hz. Force data were paired to match the kinematic data using the pedal angle. Forces were transformed from the reference frame of the pedal into the inertial reference frame. Inverse dynamic calculations determined the joint moments/power from the hip, knee, and ankle. Data were processed using a custom MatLab program (MathWorks Inc., Natick, MA, USA).

Rigid segment models of the crank, foot, leg, and thigh were generated. Hip position was determined based on the location of the anterior superior iliac spine assuming constant offset measured during the static trials. Linear and angular velocities and accelerations of the limb segments were determined by finite differentiation of position data with respect to time. Segmental mass proportions, center of mass locations, and radii of gyration were estimated from anthropometric tables. Joint moments of the ankle, knee, and hip were calculated through use of angular accelerations of the segments, normal and tangential pedal forces, and acceleration of segmental center of gravity. Joint powers were then calculated by the product of joint angular velocities and joint moments. Relative joint contribution was calculated as the percentage contribution to the total joint powers.

Statistical analysis

Descriptive statistics were compared using two-tailed Students t test ($\alpha = 0.05$). Between-group differences in VO_{2max} and lactate threshold were determined by two-way ANOVA (group × exercise mode). Differences in outcome variables (oxygen consumption, HR, RER, RPE, watts, and joint contributions) during submaximal cycling were determined through two-way repeated measures ANOVA (group × work rate). Least Significant Difference post hoc comparison was performed for all significant main effects ($\alpha = 0.05$). All statistics are reported as mean ± SE. The level for significance was set a priori at α 0.05.

Results

Subject characteristics

The HLT group had more cycling experience (3.9 ± 0.8 years) compared with the LLT group (2.0 ± 0.5 years) ($p < 0.05$). However, there was no significant difference in age (HLT: 30.3 ± 1.0 years; LLT: 26.3 ± 3.0 years), height (HLT: 175.4 ± 1.5 cm; LLT: 176.0 ± 2.7 cm) ($p > 0.05$ for all comparisons). Although not statistically different, the HLT group had on average 11.3% higher body mass compared with the LLT group (HLT: 76.1 ± 3.2 kg; LLT: 67.9 ± 2.4 kg, $p > 0.05$).

VO_{2max} (i.e. between groups and between cycling and running on a 10% grade)

There were no differences in VO_{2max} values expressed as absolute values (i.e.; L/min) between groups during maximal cycling or running (Table 1; all $p > 0.05$). However, relative VO_{2max} when running (mL/kg/min) was lower in the HLT group compared with the LLT group (Table 1; $p < 0.05$). Within groups, there were no differences between cycling and running in maximal values (Table 1; all $p > 0.05$).

Comparison of LT (i.e. between groups and between cycling vs running on a 10% grade)

There was no difference between HLT and LLT groups while running on a 10% grade (HLT: 82.3 ± 2.5%; LLT: 82.8 ± 2.3%, $p > 0.05$) (Table 2). However, LT while cycling was higher in the HLT group (80.2 ± 2.1%) compared with the LLT group (70.3 ± 2.9%) ($p < 0.05$). Furthermore, the HLT group had lower blood lactate concentration while cycling at 80 and 90% of VO_{2max} compared with the LLT group ($p < 0.05$) (Fig. 1). The HLT group cycled at 119 ± 5, 155 ± 6, 191 ± 8, 228 ± 9, 265 ± 10, and 301 ± 11 W during cycling lactate threshold testing. The LLT group cycled at 116 ± 6, 152 ± 7, 186 ± 8, 221 ± 9, 256 ± 11, 290 ± 12 W (40, 50, 60, 70, 80, and 90% VO_{2max}, respectively); there were no between-group differences in power output at any relative work rate ($p > 0.05$). Additionally, as work rate progressively increased, RPE and RER increased in both groups ($p < 0.05$) without significant differences between groups ($p > 0.05$) (Fig. 2). When running uphill both groups displayed a LT at 82–83% VO_{2max} and there was no significant difference between groups in HR and RPE responses.

Comparison of joint powers in high and low lactate threshold cyclists

Ankle joint power did not differ between groups and was relatively low (Fig. 3e; $p > 0.05$). Relative knee contribution was not significantly different between groups or across work rates (Fig. 3d; $p > 0.05$). As work rate increased, absolute knee joint power increased only in the LLT group ($p < 0.05$) without changes in the HLT group (Fig. 3c; $p > 0.05$). Relative hip contribution to power output was significantly greater in HLT at 90% VO_{2max} compared with the LLT group (Fig. 3b; $p < 0.05$) with a tendency to also be different at 80% VO_{2max} ($p = 0.07$). In both HLT and LLT absolute hip joint power increased with work rate ($p < 0.05$; Fig. 3a).

Discussion

The present study compared HLT and LLT cyclists to determine if the reduced stress previously observed (Coyle et al. 1988) in the knee extensor muscles of HLT cyclists is related to their increased relative contribution of the hip extensor

Table 1 Maximal oxygen consumption testing between high lactate threshold (HLT) and low lactate threshold (LLT) groups during cycling and running on a 10% grade

	HLT		LLT	
	Cycling	Running	Cycling	Running
Absolute VO_{2max} (L/min)	4.57 ± 0.17	4.47 ± 0.13	4.42 ± 0.15	4.49 ± 0.16
Relative VO_{2max} (mL kg^{-1} min^{-1})	60.3 ± 2.0	58.7 ± 1.3*	64.9 ± 1.6	65.9 ± 2.2
Heart rate max (beats/min)	189 ± 2*†	184 ± 3	179 ± 3	179 ± 3
Maximal RER	1.10 ± 0.01	1.09 ± 0.02	1.10 ± 0.01	1.07 ± 0.02
Maximal RPE	18 ± 1	18 ± 1	18 ± 1	18 ± 1
Work rate at VO_{2max} (W)	359 ± 16	–	326 ± 17	–

RER respiratory exchange ratio, *RPE* rating of perceived exertion

*Significant difference ($p < 0.05$) between HLT and LLT within same exercise mode. †Significant difference ($p < 0.05$) between cycling and running within same group

Table 2 Results of lactate threshold (LT) testing between high lactate threshold (HLT) and low lactate threshold (LLT) groups during both cycling and running on a 10% grade

	HLT		LLT	
	Cycling	Running	Cycling	Running
LT_{VO_2} (L/min)	3.68 ± 0.21	3.73 ± 0.18	3.10 ± 0.15*†	3.71 ± 0.13
LT % VO_{2max}	80.2 ± 2.1	82.3 ± 2.5	70.3 ± 2.9*†	82.8 ± 2.3
LT heart rate (beats/min)	162 ± 4	164 ± 3	152 ± 7*†	168 ± 4
LT work rate (W)	263 ± 9	–	221 ± 14*	–

*Significant difference between HLT and LLT within same exercise mode. †Significant difference between cycling and running on a 10% grade within same group

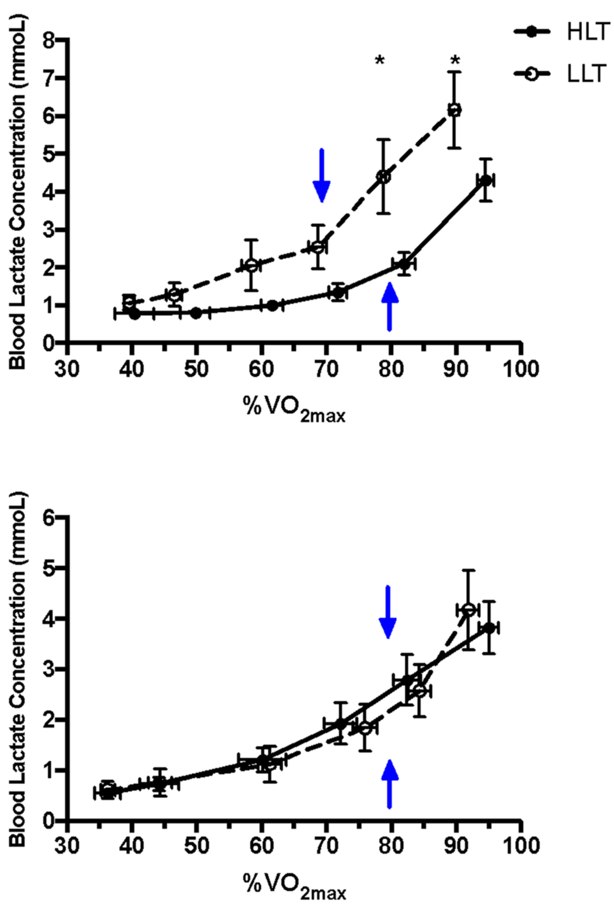

Fig. 1 Blood lactate concentration during lactate threshold testing during **a** cycling and **b** uphill running (mean ± SE). Solid lines with closed symbols represent the high lactate threshold (HLT) group and dashed lines with open symbols represent the low lactate threshold (LLT) group. Blue arrows indicate LT_{VO_2}. *Significant difference between groups at that work rate

muscles during high-intensity cycling (60–90% VO_{2max}; 175–360 W). The present study found that absolute knee joint power increased with work rate in LLT cyclists but not in HLT cyclists (Fig. 3c). Moreover, the HLT group exhibited significantly greater relative hip power contribution to total power generated at 90% VO_{2max} compared with the LLT group (Fig. 3b). These data agree with the hypothesis that HLT cyclists can produce greater power at LT by exhibiting greater relative hip power compared with LLT cyclists.

In well-trained cyclists with equally high VO_{2max}, those with LLT during cycling can sometimes achieve a higher LT during uphill treadmill running which suggests that the reduced LT is cycling-specific (Coyle et al. 1988). We (Coyle et al. 1988) and others (Lucia et al. 2000) have speculated that some well-trained cyclists have the potential to spread the work more effectively across multiple joints, and subsequently a greater muscle mass, during submaximal cycling which could, in turn, explain their reduced fatiguability. As such, in the present study, when total power output increased there was no change in knee joint power in HLT cyclists, but large increases in knee joint power of the LLT cyclists (Fig. 3). These data suggest that HLT cyclists adopted a cycling strategy which increases power production from the hip during submaximal cycling (90% VO_{2max}). This ultimately reduces the stress on the knee extensors, potentially contributing to their lower blood lactate concentrations (Fig. 2) and ultimately high LT while cycling.

The higher relative hip joint contribution in HLT compared with LLT cyclists has been observed in prior comparisons of elite cyclists with amateur recreational cyclists (Aasvold et al. 2019). However, other studies which have attempted to compare joint powers between groups of cyclists have found varying results (Bini et al. 2014; Ohashi et al. 2007), likely due to the subject population and work rates chosen for comparison. Prior studies have compared groups which differed in both maximal oxygen consumption, power outputs, and lactate threshold (Aasvold et al. 2019), or failed to report the relative work rates (Bini et al. 2014; Ohashi et al. 2007). Therefore, subjects either exercised at different absolute work rates (Aasvold et al. 2019) or potentially different relative oxygen consumptions (Bini et al. 2014; Ohashi et al. 2007). Due to the similar absolute VO_{2max} values between the groups in the present study, it was possible to make biomechanical comparisons at work rates eliciting the same absolute and relative work rates, thus limiting the confounding effects that differing absolute and relative work rates can have on joint powers (Ericson 1986, 1988). In the current study, and prior research (Aasvold et al. 2019), subjects were compared at work rates relative to maximal oxygen consumption or lactate threshold and both found greater relative hip joint contribution in the more 'experienced' cyclists. Conversely, when studies compared experienced cyclists with a higher VO_{2max} and novice cyclists at the same absolute work rates which were a low percent of maximum for the experienced cyclists, the experienced cyclists displayed higher relative knee joint contribution and lower relative hip joint contribution (Ohashi et al. 2007). It seems that in the trained cyclist, a higher relative hip joint contribution may not have been necessary when cycling at low intensities (e.g., 60% VO_{2max}; Fig. 3b) in the present study, which is supported by prior research (Ohashi et al. 2007). Therefore, rather than increasing power production from both the knee and hip joints, the HLT cyclists rely more on increasing hip joint power to accommodate increases in work rate.

While the HLT and LLT cyclists were separated based solely on physiological outcomes (i.e. LT) the HLT cyclists did have almost double the years cycling experience compared with the LLT cyclists (3.9 vs 2.0 years; $p < 0.05$). There is still debate whether high levels of experience will result in common cycling patterns or techniques, as

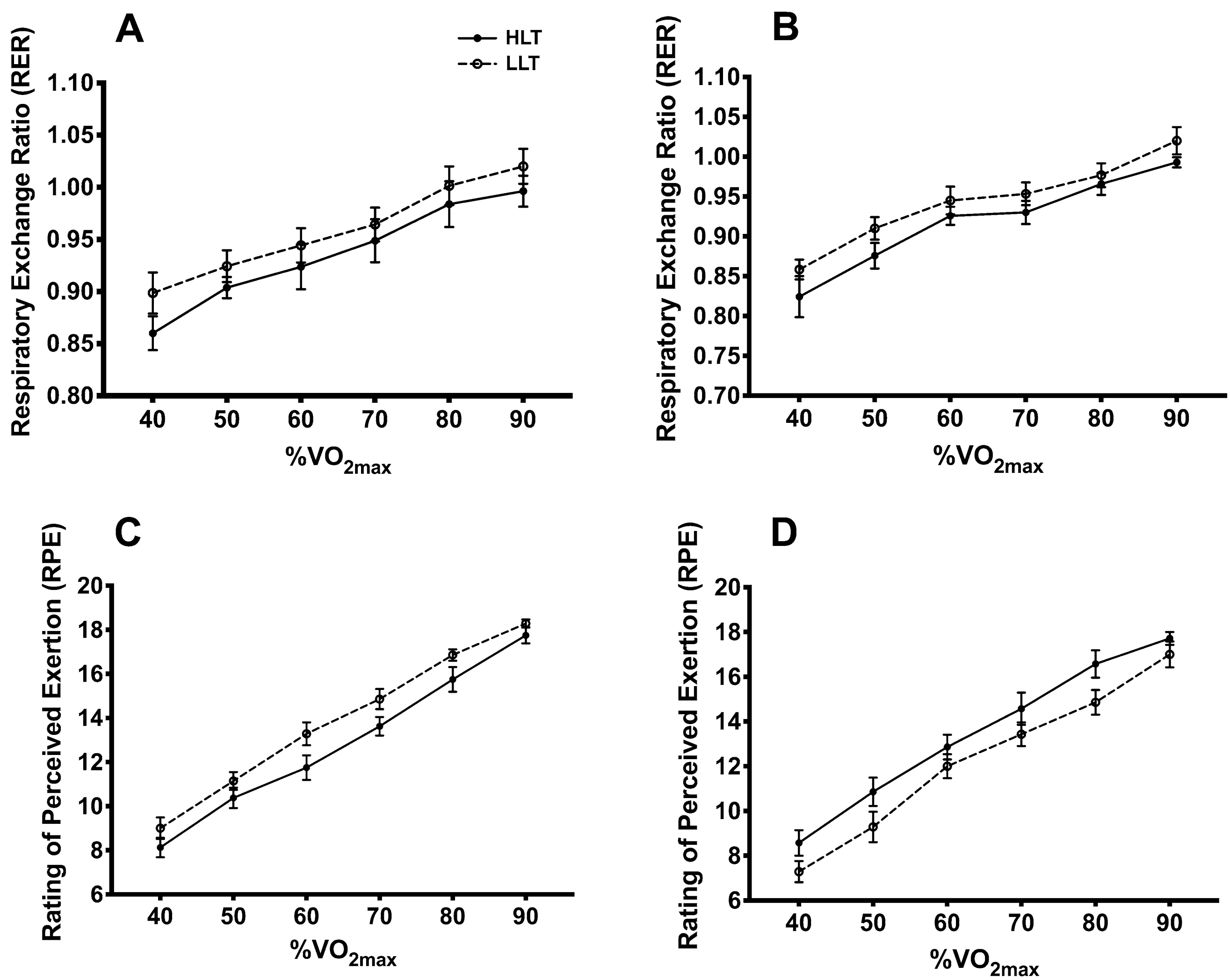

Fig. 2 Respiratory exchange ratio (RER) and rating of perceived exertion (RPE) during cycling (**a**, **c**) and running on 10% grade (**b**, **d**) during LT_{VO_2} testing in both the high lactate threshold (HLT) and low lactate threshold (LLT) groups (mean ± SE). Solid lines with closed circle represent the HLT group and dashed line with open symbols represent the LLT group. There were no significant differences between groups at any work rate (i.e. % VO_{2max}) ($p > 0.05$)

high-level cyclists with similar VO_{2max} and ~ 7 years' professional experience with an average of ~ 30,000 km/year have heterogenous muscle recruitment patterns while cycling (Hug et al. 2004). However, when comparing highly specialized professional cyclists (e.g. climbers vs time-trialists) differences in cycling technique do emerge, despite similar VO_{2max} and submaximal lactate responses (Lucia et al. 2000). Whether the added years of experience led to the differences in hip joint contribution in the present study is still unknown.

Prior research has hypothesized that an increased ability to recruit additional muscle mass during submaximal cycling might increase LT (Coyle 1995; Coyle et al. 1988). If more muscle mass is recruited to share in a given amount of work, the metabolic work and oxygen consumption per fiber and also per mitochondria, is reduced, leading to lower glycogenolysis and lower overall lactate production during submaximal exercise (Coyle et al. 1988; Holloszy and Coyle 1984). Rough calculations of the number of kg of muscle sharing in the work rate, based upon calculation of total glycogen oxidation and the change in glycogen concentration in the vastus lateralis, were previously used to estimate that cyclists with a high LT are able to recruit 20% more muscle mass than low LT cyclists (Coyle et al. 1988; Coyle 1995). In the present study, the higher relative hip joint contribution at 80% ($p = 0.07$) and 90% of VO_{2max} ($p < 0.05$) in the HLT compared to LLT cyclists could reflect an increased ability to 'spread the metabolic work' to a larger total muscle mass by increasing power output from the hip muscles.

The subjects selected for this study all had an equal VO_{2max} when cycling and running and furthermore the absolute VO_{2max} was similar in HLT and LLT (Table 1). However,

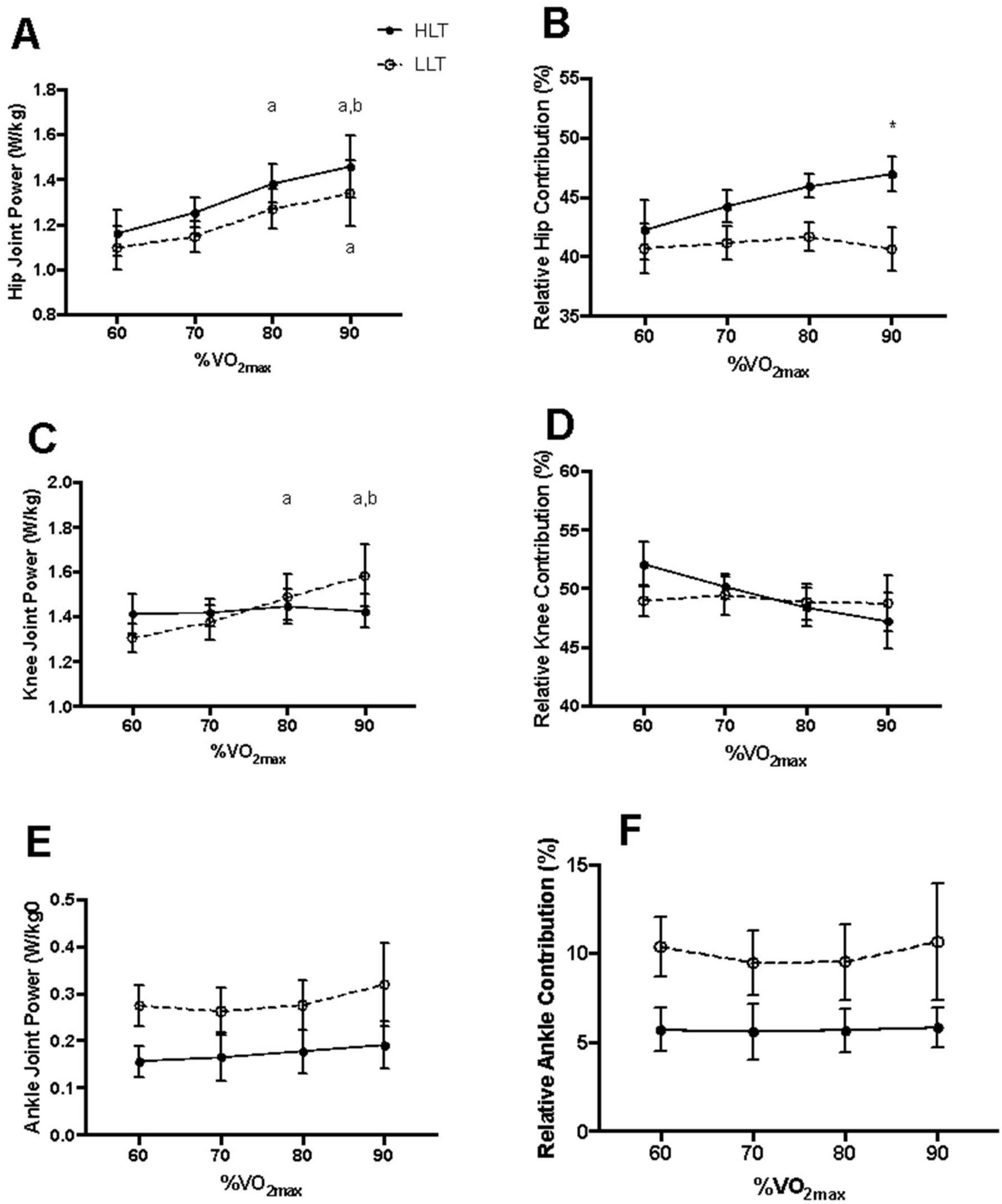

Fig. 3 Between group comparison of joint powers while cycling and relative joint contribution with increases in work rate (mean ± SE). **a**, **b** Hip; **c**, **d** knee; **e**, **f** ankle. Solid lines with closed symbols represent the high lactate threshold (HLT) group and dashed line with open symbols represent the low lactate threshold (LLT) group. *Between group differences at that work rate. [a]Significant difference between 60% VO_{2max} work rate, [b]Significant difference compared with the 70% VO_{2max} work rate

although not statistically significant, the HLT group tended to be older and heavier (e.g.; 10–13%) and they displayed an 11% lower relative VO_{2max} while running, compared with the LLT group ($p < 0.05$). The slightly higher body weight in the HLT group may have been accompanied with increased leg muscle mass and might have contributed to their higher LT when cycling but not when running. Although possible, we have no reason to think that having slightly more leg muscle by itself, as HLT might have possessed, would alter the relative joint power contributions of the hip as joint powers were normalized to body mass to account for variations in body mass (Fig. 3).

In conclusion, it appears that HLT cyclists exhibit a greater relative hip contribution to power output during cycling at 90% VO_{2max}. These observations support the theory that lactate production during cycling can be reduced by spreading the work rate over a greater muscle mass when cycling by increased reliance on relative power production from the hip musculature during extension.

Author contributions BKL and EFC conceived the research and designed the experiment; BKL, HMB, EV, ASW, CKC, and JDA recruited subjects and performed experiments; BKL and EFC interpreted results of experiments; BKL prepared figures, analyzed data, performed statistical analyses, and drafted manuscript; BKL, HMB, EV, ASW, CKC, JDA, and EFC edited, revised, and approved final version of manuscript.

Data availability Data can be made available upon reasonable request to the corresponding author.

Code availability Code used for data analysis can be made available upon reasonable request to the corresponding author.

Compliance with ethical standards

Conflict of interest As a matter of Financial Interests Disclosure, E. F. Coyle owns equity in Sports Texas Nutrition Training and Fitness, Inc., a company that consults on training and nutrition. Author Anthony Wolfe was affiliated with the University of Texas at the time of data collection and analysis and is currently employed by the Gatorade Sports Science Institute, a division of PepsiCo, Inc.

Ethics approval All procedures performed in the study was done so in accordance with the ethical standards of the University of Texas at Austin and with the 1964 Declaration of Helsinki. This study was approved by the University of Texas at Austin Institutional Review Board.

Consent to participate All subjects provided verbal and written informed consent before participating in this research study.

Consent for publication All subjects provided verbal and written informed consent for publication of data presented within this research study as part of their informed consent form.

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