SUMMARY
The purpose of this study was to identify relationships between muscle coordination patterns and factors affecting muscle coordination to explain changes in overall mechanical efficiency ($\eta_{o}$). Surface electromyography from ten leg muscles, kinematics and pedal forces were measured at a range of workloads. Principal component (PC) analysis was used to establish instantaneous muscle coordination, kinematic and pedal force patterns associated with high and low $\eta_{o}$. The $\eta_{o}$ was maximized at the anaerobic threshold and was dependent on the coordination of all active leg muscles and not any one in particular. Pedal forces were consistent among cyclists and $\eta_{o}$ was independent of the direction of applied force. The results indicate that increased $\eta_{o}$ is achieved through coordinated contraction of muscles crossing the same joint, sequential peak muscle activation from knee to hip and ankle and a reliance on multiple muscles to produce large joint torques. The findings imply that training near the anaerobic threshold in cycling will maximize the rider’s exposure to high $\eta_{o}$ muscle coordination and kinematics.

INTRODUCTION
Cycling is an activity that utilizes muscle coordination to apply force to the pedals. Although the crank motion is constrained there is variation in muscle recruitment with more muscles available than required [1, 2]. These variations in muscle activation and coordination are reflected in the metabolic costs [3] and mechanical power output and therefore should be apparent in the $\eta_{o}$ ($\eta_{o} = \text{mechanical work} / \text{total metabolic costs to produce the work}$ [4]). With different coordination patterns available some patterns produce maximal power while some are more efficient. The purpose of this study was to identify relationships between muscle coordination patterns and factors affecting muscle coordination to explain changes in $\eta_{o}$.

METHODS
Surface electromyography (EMG) was measured from the tibialis anterior (TA), medial gastrocnemius (MG), lateral gastrocnemius (LG), soleus (Sol), vastus lateralis (VM), rectus femoris (RF), vastus lateralis (VL), biceps femoris (BF), semitendinosus (ST) and gluteus maximus (GM) in nine experienced competitive cyclists at power outputs representing 25, 40, 55, 60, 75 and 90% $\text{VO}_{2\text{max}}$. The EMG was resolved into intensities ($I_{\text{EMG}}$) [5] and normalized to the mean $I_{\text{EMG}}$ for each participant for each muscle. The total EMG intensity ($I_{\text{tot}}$) was given by the sum of the $I_{\text{EMG}}$ across all muscles for each pedal cycle and was used as a proxy for metabolic power [6]. The ratio of mechanical power output to $I_{\text{tot}}$ was therefore used to estimate $\eta_{o}$.

Oxygen and carbon dioxide gas exchange, kinematics, pedal forces, mechanical power output, cadence and heart rate were also measured. Pedal efficiency ($\eta_{p}$) was determined as the ratio of effective (normal) to resultant force on the crank arm. PC analysis was used to establish muscle coordination, kinematic and pedal force patterns [7]. The most important features of the coordination patterns for the $I_{\text{EMG}}$ were explained by their foremost PCs. The relationships between the muscle coordination patterns ($I_{\text{PC}}$) and the following factors: pedal forces, limb kinematics, power output, $\eta_{p}$ and $\eta_{o}$ were determined. The $I_{\text{EMG}}$ patterns were reconstructed using the first ten $I_{\text{PC}}$ that describe the major features of the coordination that occurred with the highest and lowest of each mechanical factor (power output, $I_{\text{tot}}$ or $\eta_{o}$). Patterns of pedal forces, $\eta_{p}$ and limb kinematics were similarly reconstructed from their first five PCs.

RESULTS AND DISCUSSION
Mechanical power output
From the reconstructed patterns there was relatively smaller contribution of GM and RF, and relatively greater contribution of TA, MG, LG Sol, ST and BF at lower powers and this circumstance was reversed at higher powers. Higher power outputs were associated with increased effective force during the downstroke and more negative effective force during the upstroke (opposite the direction of crank arm rotation). Also there was very little force on the pedal across top dead centre of the pedal rotation where RF and TA were the only muscles showing noticeable increases in $I_{\text{EMG}}$. In addition, the first 45 degrees of the pedal cycle, where pedal forces and power outputs were increasing, there was very little VM, VL or GM $I_{\text{EMG}}$. Therefore the RF and TA appeared to be keys to power production by initiating knee extension and maintaining appropriate joint angles early in the pedal cycle. The Sol was at its greatest $I_{\text{EMG}}$ at the bottom of the downstroke when GM was also at its maximum. With a higher percentage of slow type muscle fibres than MG and LG [8], the Sol is used more at high resistances [7]. It was therefore well suited to stabilize the ankle joint and work with the GM to transfer power to the pedal similar to the simulation findings by Neptune [9].

There was increased $\eta_{p}$ at higher powers resulting from an increased $\eta_{p}$ during the upstroke and across the top dead centre. The hip angles for the high power output were smaller across the top of the pedal cycle and larger across the bottom of the pedal cycle than for the low power output, whereas the knee angles were similar throughout. The ankle angles for the high power outputs were 5-14 degrees more dorsiflexed than for the low power outputs throughout the pedal cycle.

Total EMG intensity, $I_{\text{tot}}$

The $I_{\text{tot}}$ correlated strongly with the power output ($r=0.86$), and so many of the relations between muscle power output and muscle coordination were matched by similar relations between $I_{\text{tot}}$ and coordination. The GM had the largest $I_{\text{EMG}}$
range between conditions followed by RF, BF, VM and VL. The MG showed little change in I_{EMG} between conditions with LG, Sol and TA only slightly greater. The large range of I_{EMG} shown by the GM provided evidence supporting its role as a significant contributor to high power production [10].

The reconstructed patterns showed the greatest increases in the RF and GM I_{EMG} as well as timing advances for the VM, VL and BF for high I_{tot}. High I_{tot} was also associated with a larger peak effective force during the downstroke and similar effective force during the upstroke. The primary difference in η occurred at the top of the pedal cycle where it was elevated for higher I_{tot}. Hip angles were larger throughout the pedal cycle and the ankle was more dorsiflexed during the downstroke for higher I_{tot} compared to lower I_{tot} while the knee angles were similar for both.

Overall efficiency, η

The η was maximized at 55-60% VO_{max}. There was a significant covariation between η and I_{PC1}, I_{PC3}, I_{PC5}, I_{PC7} and I_{PC8} therefore the η was strongly related to muscle coordination patterns. For example at maximum η (55-60% VO_{max}) the ratio I_{PC3} / I_{PC1} was in its mid-range (Figure 1), and so η was very sensitive to I_{PC3} / I_{PC1} with ratios too high or too low being associated with low η.

![Overall Mechanical Efficiency](image)

**Figure 1:** Scatter plot with mean ± SEM for overall mechanical efficiency (x-axis) and the EMG muscle intensity principal component (y-axis) for 25, 40, 55, 60, 75 and 90% VO_{max} conditions. Note that the SEM in the y-axis is very small.

The coordination pattern for high η had a more even distribution of I_{EMG} across all muscles, whereas for low η it displayed large amounts of activity in GM, RF and short bursts of VM and VL. At high η the I_{EMG} for the key power producing muscles (VL, VM and GM) were more evenly distributed during the downstroke. Also, high η was associated with a regular progression of activity between the muscles (initially VM and VL synchronously, followed by GM, then Sol, and finally LG, MG, ST and BF synchronously). Conversely, with low η the muscle groups were activated less in concert and the I_{EMG} of VL and GM were almost 90˚ apart. The timing of the I_{EMG} for GM and Sol was earlier at high η implying that these muscles provided force on the pedal for more of the power producing downstroke. Given the smooth and even distribution of I_{EMG} and synchronization of peak activity, it is possible that the coordination pattern for high η results in smoother shifts from net knee to net hip joint moments that occur during the downstroke [11].

There was little difference in pedal forces and no difference in η between high and low η. The hip and knee angles showed negligible difference between high and low η. The ankle angle was more plantarflexed during the downstroke and more dorsiflexed during the upstroke for the high η.

CONCLUSIONS

This study has shown significant associations between the muscle coordination, forces acting on the pedals, mechanical crank power, total EMG intensity and overall mechanical efficiency. Coordinated muscle recruitment is a key factor in determining the mechanical efficiency of limb movement [12]. Similarly, this study demonstrates that overall mechanical efficiency in cycling appears to be dependent on the activation levels, timing and coordination of all the active leg muscles. The results indicate that increased η is achieved through coordinated contraction of muscles crossing the same joint, sequential peak muscle activation from knee to hip to ankle and a reliance on multiple muscles to produce large joint torques. With consistency in pedal force application, the η seems to be independent of the direction of applied force.

In practical terms these results may have implications on training for cycling as training at 55-60% VO_{max} may maximize the rider’s exposure to high-efficiency muscle coordination patterns and kinematics. As the muscle coordination patterns employed at each resistance are different, training at event-specific workloads would maximize the use of muscle coordination patterns that would be realized in competition.

ACKNOWLEDGEMENTS

We thank Sabrina Lee and Manku Rana for helping with data collection, Max Donelan for the use of the metabolic cart, Dan Marigold for the use of the electronic goniometer data collection, Max Donelan for the use of the metabolic cart.