Q FACTOR IN CYCLING:

KINEMATIC AND PHYSIOLOGICAL EFFECTS

by

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A thesis submitted to the

University of Birmingham

for the degree of

DOCTOR OF PHILOSOPHY

Human Movement Research Group

School of Sport, Exercise and Rehabilitation Sciences

University of Birmingham

September 2013

ABSTRACT

Q Factor represents the horizontal distance between pedals on a bicycle, measured from the outside edge of each crankarm. The action of pedalling is based upon human gait, which utilises a step width lower than standard Q Factors (150mm for road bicycles). The aims of this thesis were to understand the kinematic and physiological effects of manipulating Q Factor. Lower Q Factors than standard afforded increased gross mechanical efficiency and individually determined optimal Q Factor (OQ) provided increased power output during laboratory time trials. Self selected Q Factor (SSQ) was lower than standard in trained cyclists and could be predicted using a simple suspension task. The use of SSQ compared with Q Factors higher and lower than SSQ provided a combination of kinematic stability and increased efficiency, lowering the risk of injury and the oxygen cost of cycling. Lower Q Factors than the standard 150mm for road bicycles provide performance and kinematic benefits that have not been examined previously. As part of the overall package of bicycle fit, individual cyclists will be able to make measurable improvements by finding and utilising their self selected Q Factor.

ACKNOWLEDGEMENTS

I would like to extend my warmest thanks and gratitude to Dr. François-Xavier Li for the excellent supervision that I have received whilst at the University of Birmingham, for which I am truly grateful. I feel extremely fortunate to have been able to complete my research with the aid of his guidance and support.

I would also like to thank my laboratory and postgraduate colleagues, including Oliver Wilson, Rebecca Randell, Jo Long, Adrian Hodgson, Borut Fonda, Rachel Turner and Amy Scarfe, as well as the technical staff Dr. Dave McIntyre and Steve Allen.

Without the help of the undergraduate researchers much of this data would not have been possible to collect, and thanks goes to Ella Hopkins, Pippa Blandford, Matt Stuart, Pete Fey, Charlotte Cawood and Sam Bennett.

In particular I would like to thank my mother, Alison Disley and also Alice Saltmarsh for their invaluable help and support during my time at Birmingham.

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1. INTRODUCTION

1.1 From walking to cycling

The modern bicycle is a machine for recreation, exercise and professional sport. Different forms of bicycle are used in a variety of disciplines, from mountain bicycles with suspension, BMX, track and road bicycles, which are all optimised for different terrains, to provide the pilot with the means of moving with maximised comfort, efficiency and speed.

The human body, through the process of nature's engineering trial by error – evolution – similarly has adapted to be able to walk and run over land with comfort, efficiency and speed (Schmitt, 2003). The bicycle is the most efficient mode of human powered transport (Jeukendrup et al., 2000) and provides a mode of travel for over four million people every single week in the UK (Department for Transport). The combination of man and machine allows us to cover distances at speeds five times that of walking with the same energy cost (Capelli et al., 1998;Davies, 1980;Kram & Taylor, 1990;Margaria et al., 1963; Pugh, 1974).

The modern bicycle in its various guises finds its genesis in the "safety bicycle" of the 1800s. This was characterised (and different from) the penny farthing due to similar sized wheels front and rear, a lower sitting position closer to the ground and a chain drive system which permitted gearing for faster speeds without the frenetic pedalling of fixed hub based cranks and pedals.

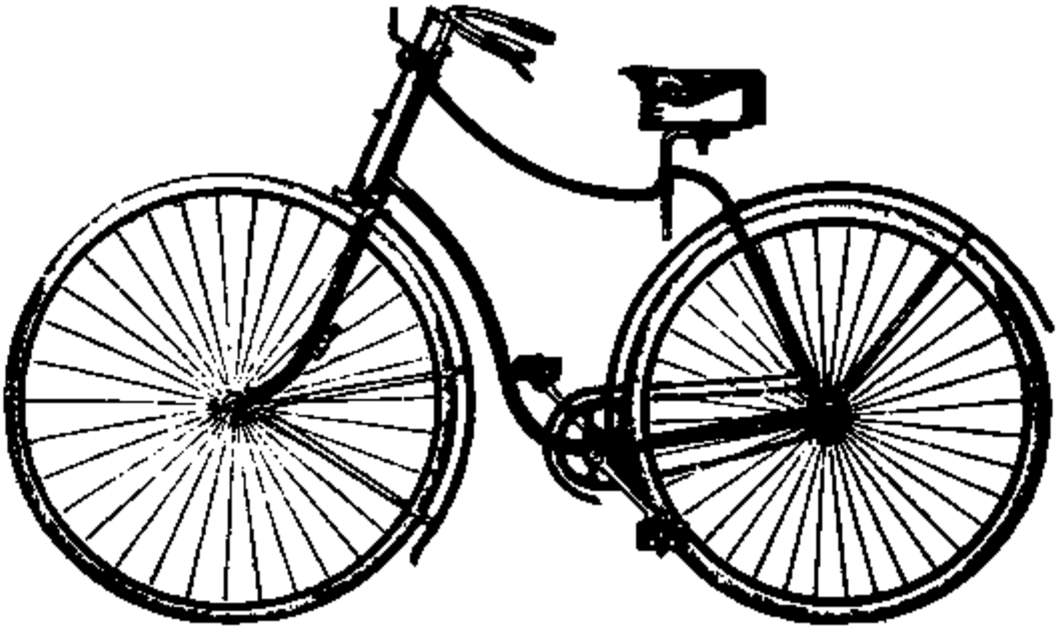

Figure 1. The Safety Bicycle (phys.uri.edu)

The design of the safety bicycle harked back to the velocipede and similar walking aids, but with the chainwheel and cranks providing propulsion. Other characteristics included a saddle for comfort and brakes (mounted front and/or rear) to modulate or curb speed. Linking the cranks and pedals to the rear wheel by use of a chain drive provided high efficiency (>95%) and allowed relatively free placement of the cranks in the bicycle frame. The location of the all important three contact points: the pedals (which are the main topic of this PhD), saddle and handlebars, has remained consistent since the safety bicycle design emerged, with minor alterations to their individual ergonomics (Berto, 2004; Herlihy, 2004).

No other mode of movement using force generated by the human body (e.g. cross country skiing, hand cranked cycles, walking and running) is as economical as leg propelled cycling on land – at around 10mph the energy expenditure for running on flat ground is approximately 2.5 times that of cycling (Goosey-Tolfret et al., 2008; MacDougall et al., 1979, Mukherjee & Samanta, 2001; Saibene et al., 1989). It is for this reason that cycling is one of the most popular forms of transport, with some countries such as Denmark reporting nearly a quarter of all journeys <5km in length being made by bicycle, and over a third of all adults using a bicycle for commuting (Cycling Embassy of Denmark, 2013). It was only natural therefore, that the exercise of cycling would follow the paths set by running, swimming and jumping by evolving into a competitive sport, as well as a recreational and practical activity.

1.2 Economy to profit

Cycle racing began informally in the 1860s with exhibition races in France and later Italy. Penny farthings were used for racing before the chain driven bicycle took prominence in the 1870s and 1880s. In the United Kingdom, the Bicycle Union (later renamed the National Cyclists' Union) was formed in 1878 in London and charged with protecting cycle sport and its organisation. In 1890, the NCU banned all racing upon open roads and sought to a restriction to closed roads and velodromes, which led to the formation of splinter groups which organised covert solo timed events (time trials) rather than bunch racing. A handbook containing secret codenames for course locations is still in use today. Internationally there was also a move towards spectator friendly closed circuit events, which evolved into the popular six day events in America and Europe, where competitors tried to complete as much distance as they could around a small circuit in six days of non-stop racing, although road racing on open roads was still common. The Union Cycliste Internationale (UCI) was formed in 1900 and continues to organise and regulate cycle sport from its base in Switzerland (www.britishcycling.org.uk; www.uci.ch).

1.3 Tour de France

The largest cycle sport event is the Tour de France, which began as a publicity stunt for the magazine *L'Auto* (www.letour.fr). The first edition of the race was in 1903 and was a brutal affair, based upon the six day events but using open France as the race course. Six stages of up to 293 miles each took the twenty-one finishers over 94 hours to complete amidst rampant cheating and accusations of barbarism by the riders about the difficult course. 2013 will mark the 100 year anniversary of *Le Tour* with twenty-one stages and a total distance of over 2,000 miles.

The Tour de France set the modern standard for road racing bicycles. Comfort and speed were prerequisites for both the competitors due to the long distances that needed to be covered as efficiently and quickly as possible. Derailleur gears (which allowed shifting into lower gear ratios for climbing and improved speeds compared with a fixed gear ratio) were in existence before their introduction to the 1937 Tour, but subsequently surged in popularity and common use as manufacturers such as Campagnolo and Simplex introduced models for consumer racing bicycles. Fixed gears are still used today in track cycling.

The emergence of competitive cycle sport also began the natural process of performance optimisation. As found in many sports where equipment plays a pivotal role in success (such as rowing, sailing and archery), the evolution of equipment design runs concurrently with improvements in training and tactical knowledge. Sport science as an emerging discipline sought to understand the limitations and possibilities for optimising performance, and cycling exercise formed a useful tool to understand physiology.

1.4 Cycling science

Ergometer cycling in a laboratory is a simple mode of exercise with which to analyse muscular activity and other parameters such as kinematic or physiological data, compared with other forms of exercise such as running and swimming. Ergometer cycling also provides an known measure of external work. For example, cycling has been used as the preferred mode of exercise to explore the effects of ergogenic aids (Hodgson et al., 2013;Laurence et al., 2012;Randell et al., 2013) or external motivation (Nakamura et al., 2010). As a common activity which most adults are accustomed to, cycling is a low risk activity for laboratory based research. Cycling is commonly used in research studies and experiments both investigating physiology in general but also effects specific to cycling, such as muscular activation (Connick & Li, 2013;Hug et al., 2013).

Even though it is low risk, injury in cycling is often difficult to quantify but has been related to kinematic instability whilst pedalling (Silberman et al. 2005, Abt et al. 2007). The knee joint has the greatest range of motion during the pedal stroke, compared with other joints such as at the hip, ankle, elbow etc., and as torque is transferred through the knee as force is applied at the pedal, knee pain is a common cycling injury (Silberman et al. 2005; Bini, Hume & Croft 2011, Wanich et al. 2007; Clarsen, Krosshaug & Bahr 2010). By making positional adjustments on the bicycle, there is potential to reduce the amount of kinematic instability whilst cycling, especially at the knee but also in other areas of high torque such as the hip and the ankle. In order to make such adjustments however it is important to understand the muscles involved during cycling.

1.5 Cycling muscles

The major movers in the pedalling action are the quadricep group and knee extensors, in particular the vastus lateralis and medialis, providing 39% of the total positive mechanical work compared with 27% for the hip extensors (Ericson 1986).

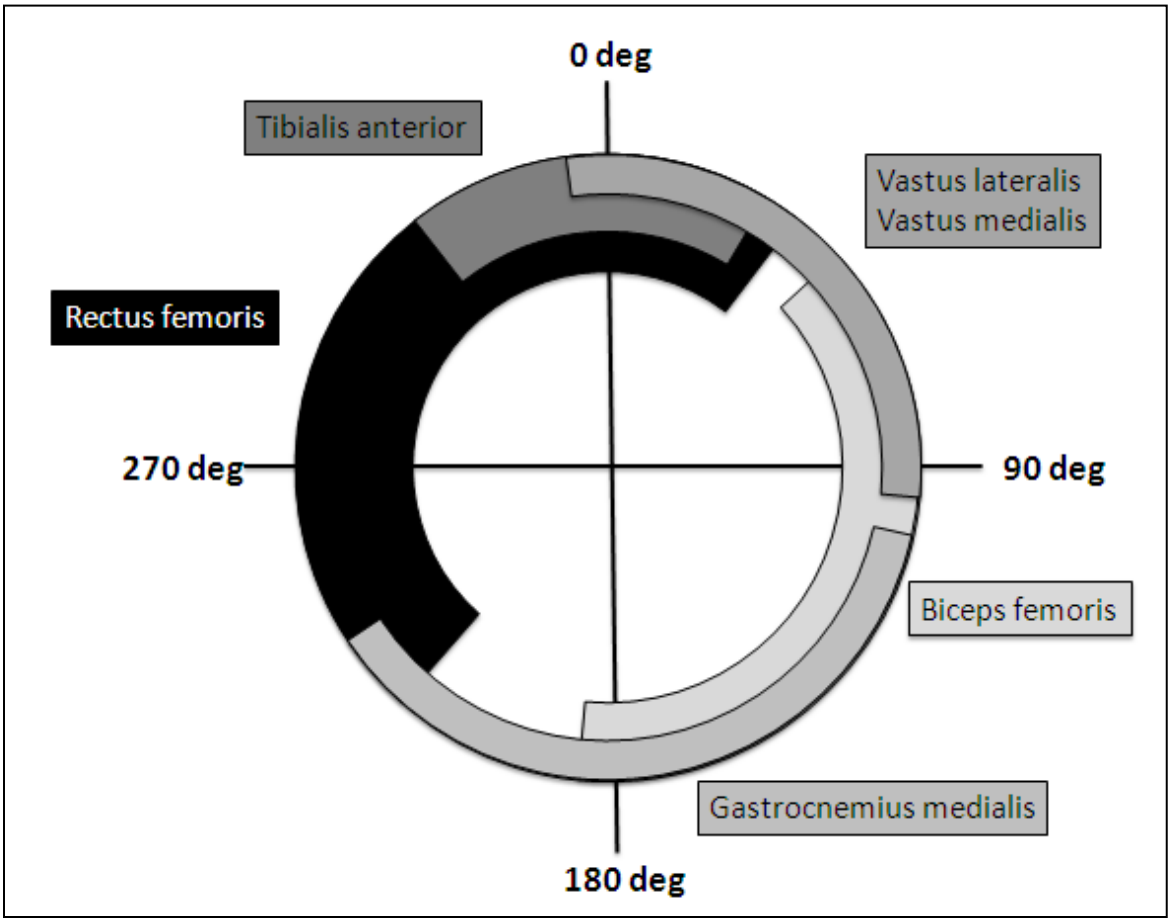

Figure 2. Periods of muscular activation during the pedal cycle. (adapted from Hug & Dorel, 2009).

During the course of one crank revolution, peak torque occurs just after 90deg (Hug & Dorel, 2009), following the activation of the vastus lateralis and vastus medialis around top dead centre (TDC) or the 12 o'clock position of the crank. As the crank moves past the point of peak torque and towards bottom dead centre (BDC), muscles of the lower leg and hamstring (e.g. the gastrocnemii, soleus, biceps femoris) serve to bring the pedal backwards and upwards before returning towards TDC. The upper and lower positions for the cranks are known as "dead centres" due to the low effective force applied in the direction of crank rotation. Previous research has found that metabolic indicators of cycling efficiency are related to mechanical indicators of force effectiveness (Leirdal & Ettema 2011), where a decrease in the force effectiveness, namely the force applied perpendicular to the crankarm results in a lower efficiency (Candotti et al., 2008). A cyclist should therefore strive to improve force effectiveness at the pedal in order to increase their efficiency, and therefore speed. This has been explored by examining cadence effects (Ettema et al., 2009) and also body position angles (Dorel et al., 2009).

1.6 Contact points

Over the years, the design of the racing bicycle and its associated components for the purpose of performance enhancement has led to developments to further improve comfort and increase speed. A popular area of study has been the height and angle of the saddle attachment for the rider, one of the three points of contact with the bicycle and an easily manipulated variable (Price & Donne, 1997;Sanderson & Amoroso, 2009). The combination of saddle height and seat tube angle fixes the location of the saddle in 2D space. Since the saddle cannot move laterally towards or away from the bicycle, these two parameters can be adjusted to provide the rider with the optimum saddle location for their individual anthropometrics. Regression equations have been calculated for the optimum saddle height based upon the characteristics of the rider, such as leg length, flexibility and inseam height (Bini et al., 2011;Peveler & Green, 2011). Saddle angle has been explored in a multisport situation such as duathlon or triathlon where a competitive athlete will run after cycling (Bisi et al., 2012;Silder et al., 2011), and so a method to optimise muscular activation and reduce fatigue for the subsequent running leg can be achieved by altering saddle angle relative to a vertical line of reference passing through the bottom bracket (most often increasing, to around 80deg).

Changes in saddle location should always be combined with an analysis of the handlebar position. In normal road cycling, the handlebar extends equilaterally from the stem before curving away and downwards, allowing the cyclist multiple hand positions for comfort.

Different positions are adopted whilst climbing:"on the tops" - in the centre of the handlebar when seated, or "on the hoods" - at the outside edges of the handlebars when out of the saddle. Whilst descending the lowest position on the handlebar is often used - "on the drops", and riding on flat terrain will be a combination of the three. During timed competitive events and multisport events, racers will often use forward extensions to their handlebars along with arm rests in order to provide them with a fourth, more aerodynamic position. The aero position changes the point of contact at the handlebars from the hands only to the elbows, forearm and hands. The reason for choosing an aero position is to reduce the aerodynamic drag force acting upon the cyclist as they cycle, and can account for up to 80% of the total forces resisting forward motion, at speeds of 25-55kph and beyond (Atkinson et al., 2003;Olds, 2001.

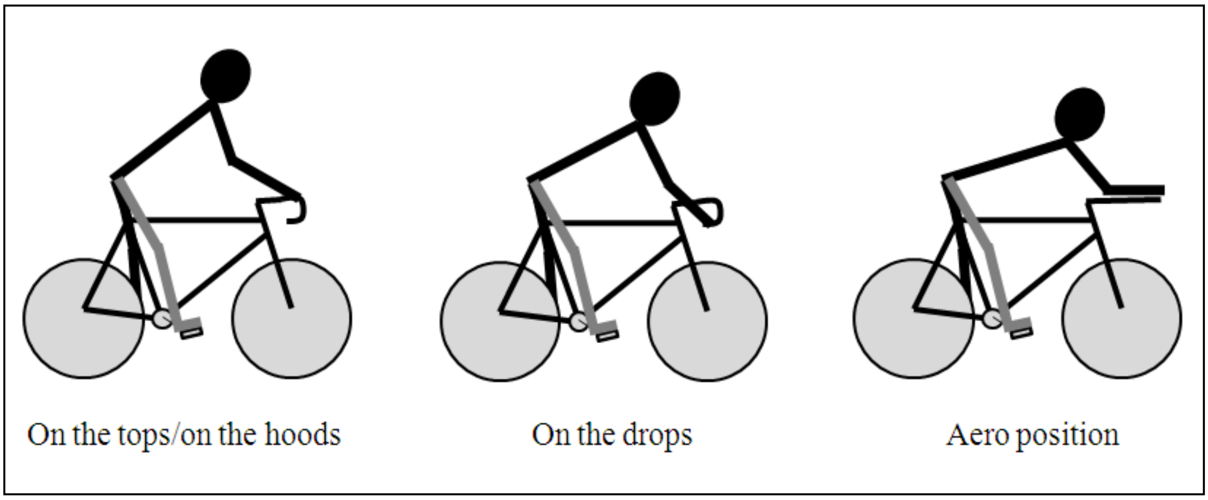

Figure 3. Positions adopted during cycling.

This improvement in aerodynamics typically comes at the cost of reduced power output. Greater strain in the lumbar region, compression of the hip flexor muscles and restrictions to the intercostal breathing musculature can result in discomfort, changes in muscular activity patterns and decrease efficiency when cycling in the aero position (Ashe et al., 2003;Brown et al., 1996;Chapman et al., 2008;Dorel et al., 2009;Savelberg et al., 2003), but the loss in power output is usually mitigated by the intended aerodynamic benefit (Grappe et al., 1998). The combination of saddle and handlebar position therefore govern the upper body angle of the cyclist, specifically the torso angle of the cyclist. A low handlebar position coupled with a steep seat tube angle can maintain the knee-hip-shoulder angle found in more upright riding and allow the cyclist to remain comfortable as well as aerodynamic and powerful.

1.7 Pedals and gait

The final point of contact for the cyclist are the pedals. The crank and pedal system was devised to make best use of the human gait action, in particular the musculature designed for knee and hip extension (another option that was developed and subsequently discarded was the treadle – a stirrup based shaft drive – that mainly relied upon hip extension). Both walking and running require knee and hip extension to enable the transition between phases, and it is the force generated by this action that the crank and pedal system seeks to harness.

The human gait cycle consists of two distinct phases: stance and swing. During the middle of the stance phase, when a single limb is loaded, full knee and hip extension is required to enter the swing phase, whereupon flexion occurs to bring the limb forward past the vertical ready to re-enter the stance phase.

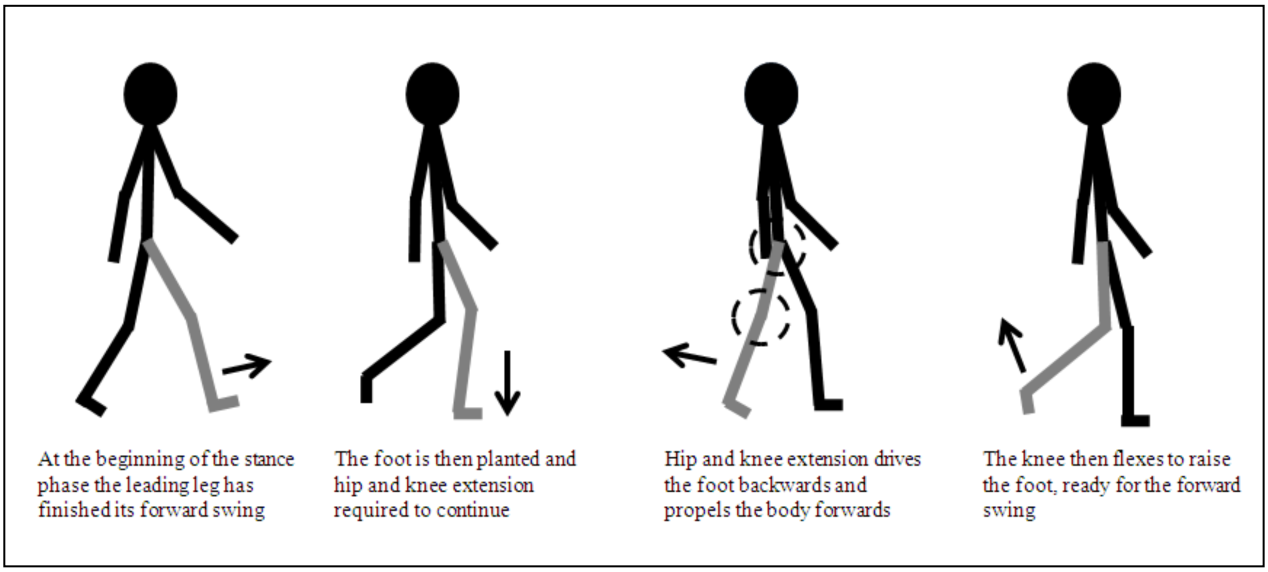

Figure 4. The stance phase of the gait cycle.

The muscles used in this part of the gait cycle are similar to the primary movers used in cycling previously described: the vastus lateralis, medialis and rectus femoris of the quadriceps group and the biceps femoris (figures adapted from Hug & Dorel, 2009;Ivanenko et al., 2004).

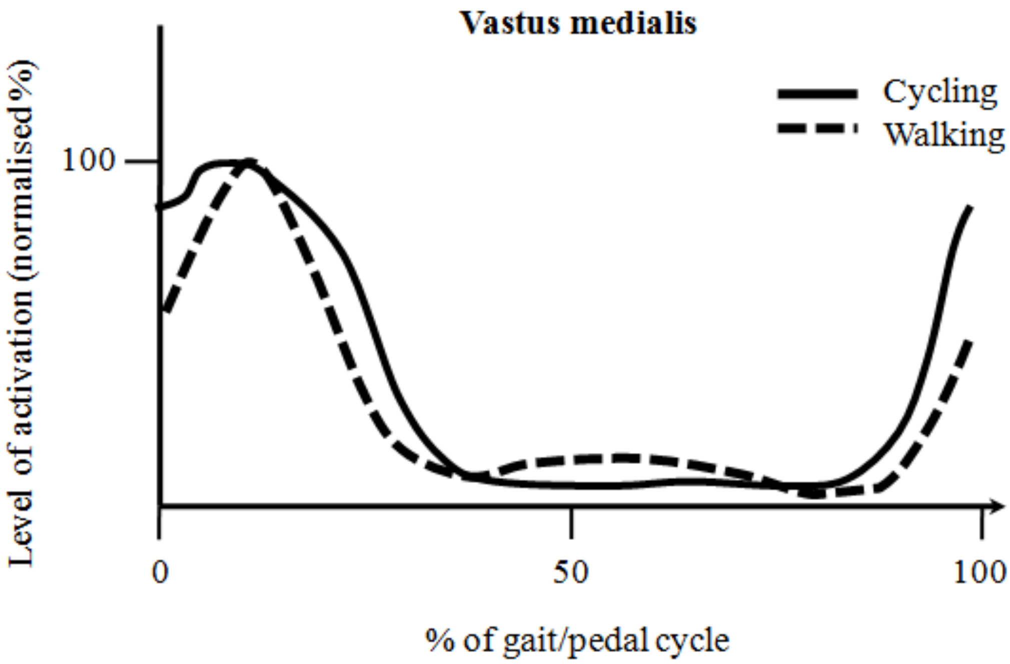

Figure 5. Muscular activity of the vastus medialis during cycling and walking

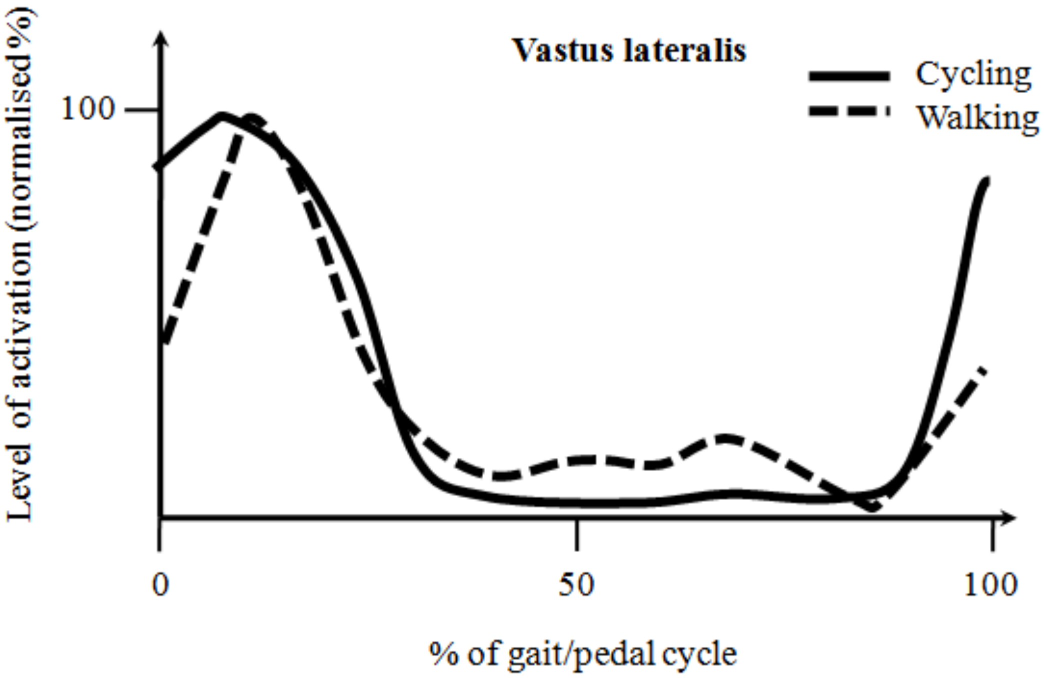

Figure 6. Muscular activity of the vastus lateralis during cycling and walking

Not only are the muscles similar, as we can see in Figures 5 and 6 the timing of activation whilst cycling is very close to that of the activation profile whilst walking, with relative peak and lowest levels of activation occurring at similar locations in the gait and pedal cycles.

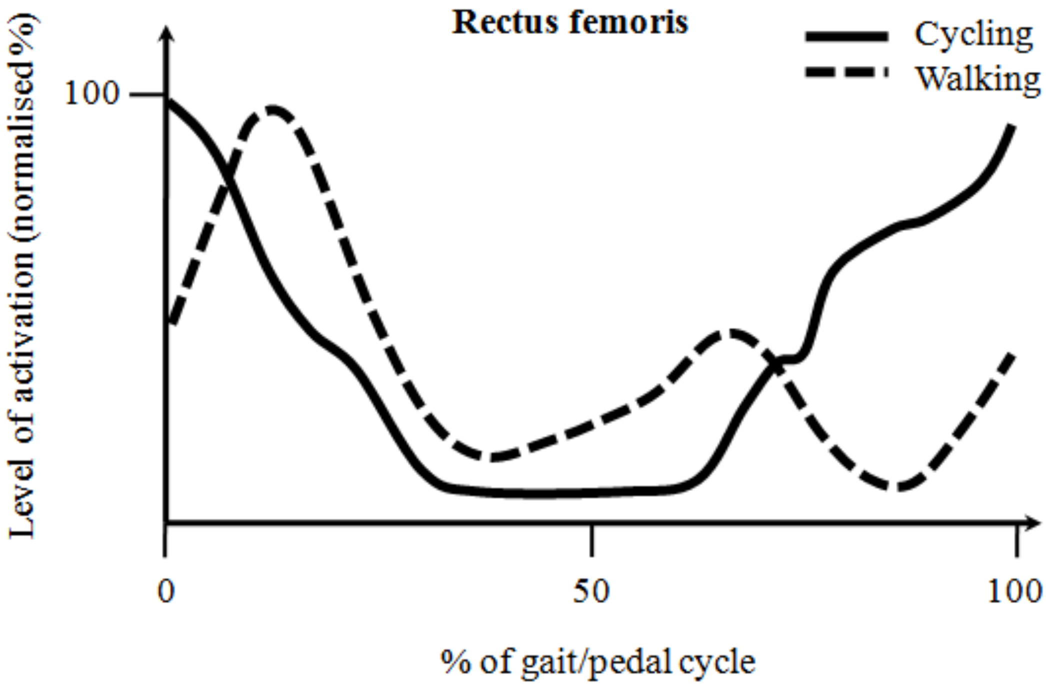

Figure 7. Muscular activity of the rectus femoris during cycling and walking

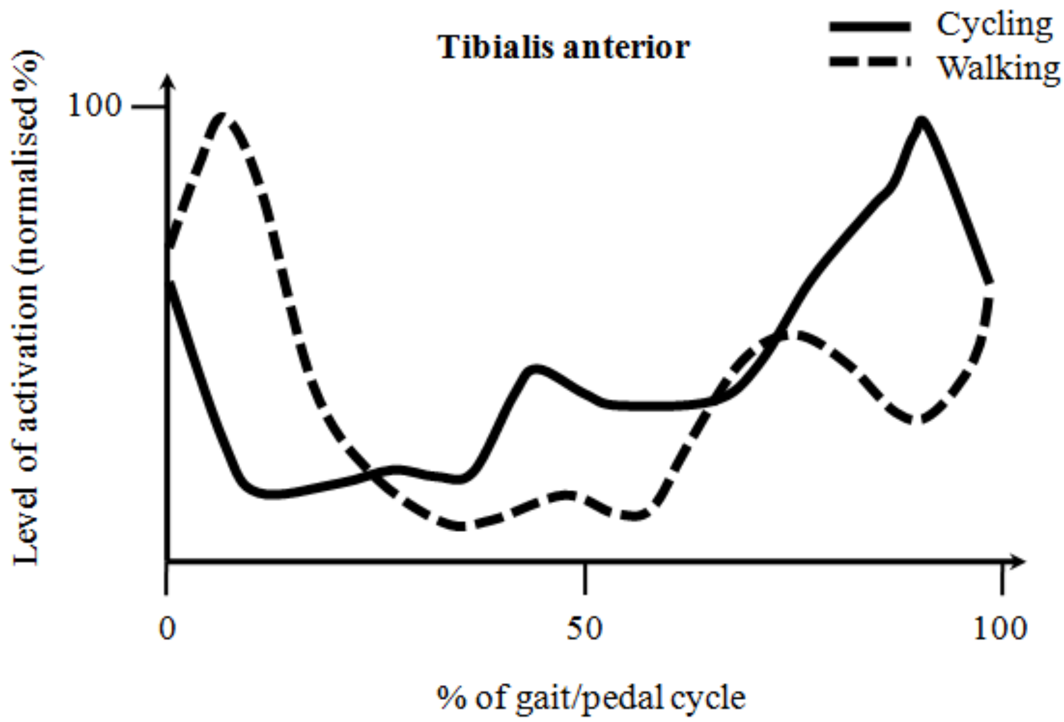

Figure 8. Muscular activity of the tibialis anterior during cycling and walking

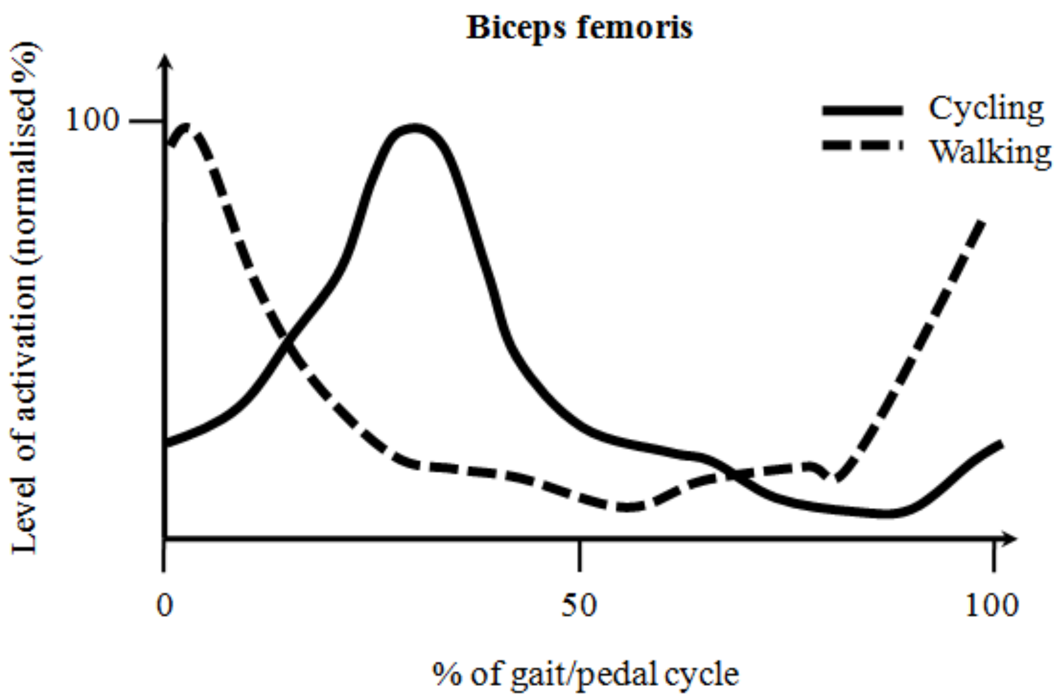

Figure 9. Muscular activity of the biceps femoris during cycling and walking

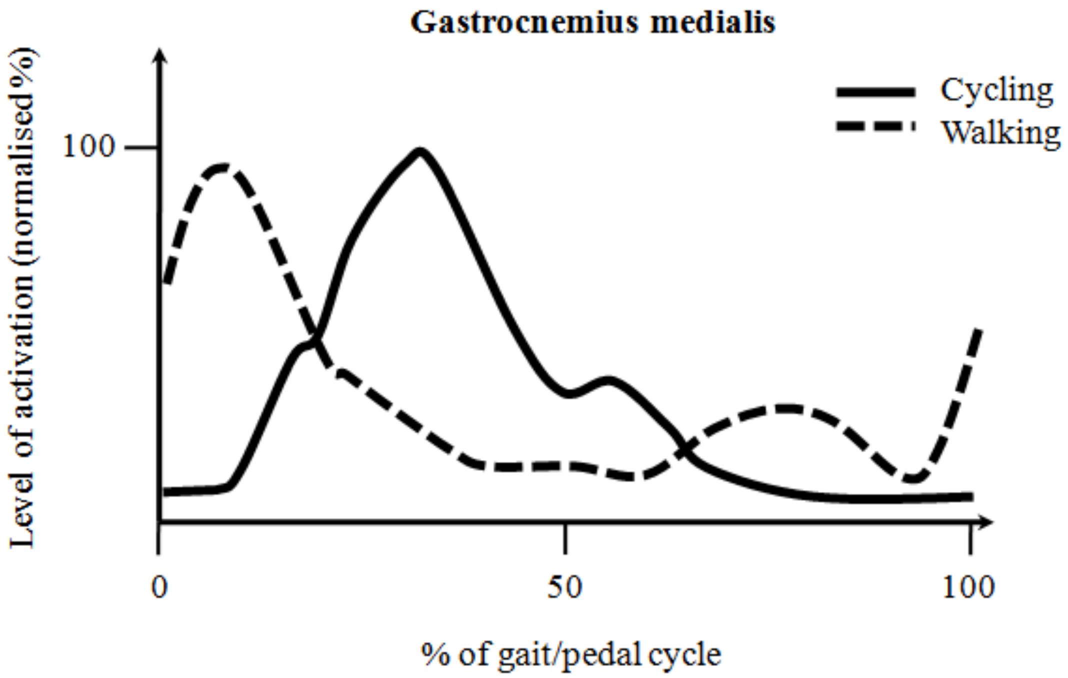

Figure 10. Muscular activity of the gastrocnemius medialis during cycling and walking

In contrast to the vasti laterali and mediali however, the rectus femoris, tibialis anterior, biceps femoris and gastrocnemius medialis do not share such a close pattern of activity between cycling and running (Figures 7-10). Instead, there appears to be a phase shift for some of the muscles: the onset of increased activation for the biceps femoris and gastrocnemius medialis occurs approximately 25% later during cycling compared with walking, whereas the tibialis anterior and rectus femoris activate 10-25% earlier, all sharing broadly similar profiles of activation but out of phase. The range of motion whilst walking is distinct from cycling, which is a constrained activity governed by the fixed and constant arc of the pedals and crankarm. Knee and hip joint angles are less acute during walking, and positive mechanical work to aid forward motion is still possible in cycling as the non dominant leg moves from 180deg through 270deg. This phase shift is likely to be due to contact time with the ground and the necessity to lift the foot off the ground at the end of contact.

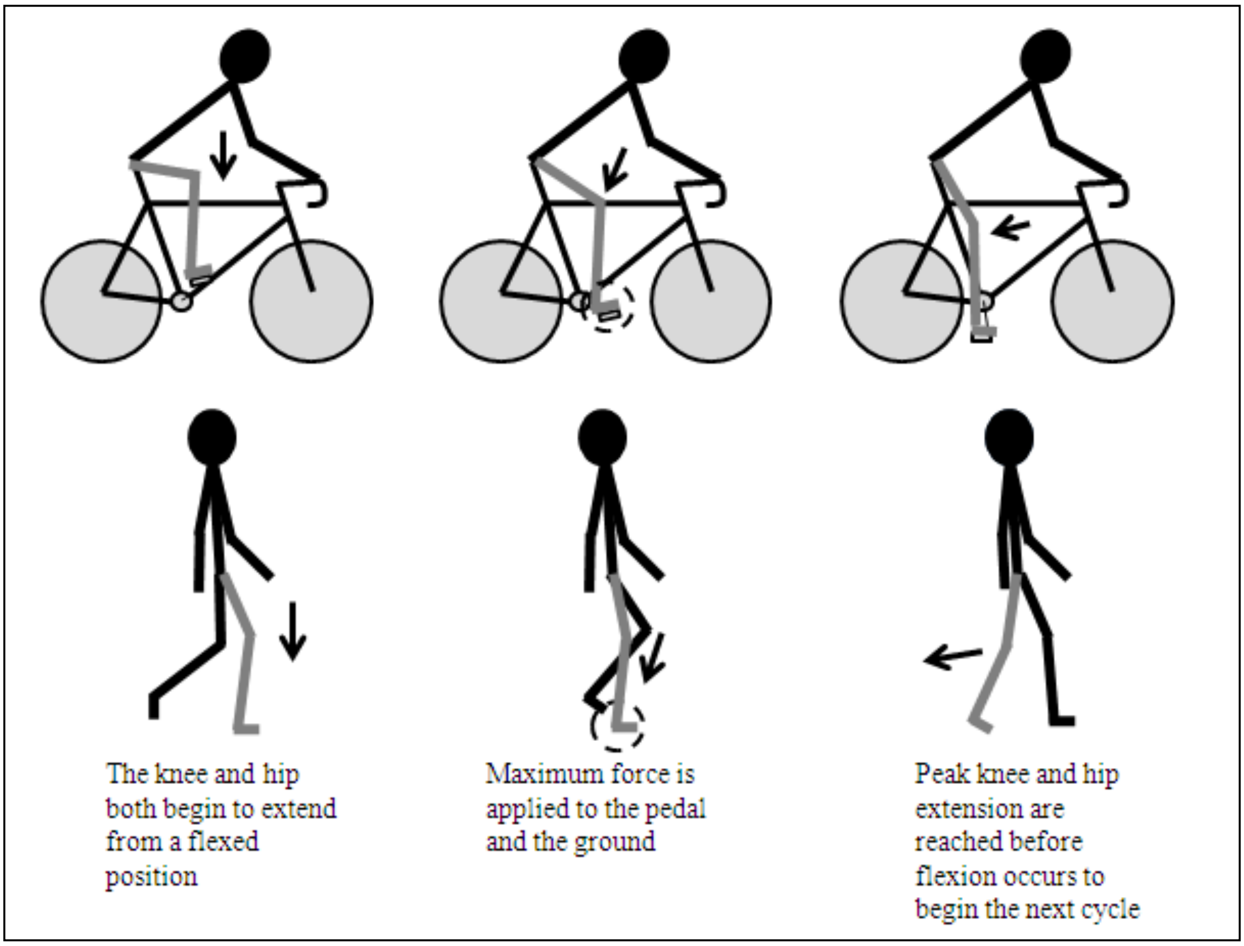

Figure 11. A comparison between the stance phase of the gait cycle and the downstroke of the pedal cycle.

The location of the pedal in 2D space along the sagittal plane follows an arc centred on the bottom bracket axle around which the crank arm rotates. Crank arm length is fixed and usually within a range of 165-180mm, causing the pedal to travel ~1.1m each rotation. Unlike the saddle and handlebars which are fixed in location, the pedal contact point is constantly moving along with the upper and lower legs. Previous studies have explored how changing the length of the crank arms might affect parameters such as maximal oxygen consumption, efficiency and aerobic/anaerobic power output (Barratt et al., 2011;Martin & Spirduso, 2001;Too & Landwer, 2000), as well as how the rate of movement of the pedal, "cadence" can affect physiological parameters and muscular activation (Candotti et al., 2009;Ettema et al., 2008). Force is created by the legs and transferred to the pedal, and in turn through to the rear wheel via the chain which propels the bicycle forward. Optimisation of the force applied at the pedal is therefore critical to effective cycling.

1.8 Step by step improvements

Early pedals were simple flat platforms upon which the foot would rest. With flat pedals, force was only able to be directed downwards, causing the non-pushing leg to be redundant until the pedal had completed its cycle, but this quickly evolved into the use of clips and leather straps in order to both keep the foot centred on the pedal, and also allow the rider to "pull up" as the foot passed the bottom of the pedal stroke and returned towards the 12 o'clock position. One technological advance that sought to achieve this was the creation of the clipless pedal, first invented in 1971 by Cinelli (Milan, Italy), with the M71 pedal. The use of the clipless pedal built upon the success of clips and straps by allowing no accidental movement of the foot, thereby increasing power transfer, as well as improving comfort as the leather strap tightened hard across the top of the shoe was removed.

In spite of the availability of a clipless pedal in the early 1970s (Cinelli M-71, Italy), worldwide success was only reached in 1985 when Bernard Hinault, that year's winner of the Tour de France, used a prototype pedal by Look (Nevers, France) which allowed automatic release of the foot, similar to a ski binding. A plastic or metal shaped body, or “cleat” was attached to the underside of the shoe, with a spring mechanism housed within the pedal. The cleat engaged with the pedal with a small amount of downward force, and was released with a twisting motion of the foot which disengaged the spring mount. Cleats were originally nailed to the shoe, and now follow universal two, three hole or four hole mounting patterns using bolts and screws. Since the turn of the century the clipless pedal has become increasingly popular for the amateur racing and also casual cyclist, far more than a typical flat pedal (Cruz & Bankoff, 2001). The cycling industry is awash with pedal manufacturers, models and makes, and dominated by a number of key players, notably Shimano (Osaka, Japan), Look (Nevers, France), Speedplay (San Diego, USA) and Time Sport International (Isère, France). Road cycling pedals and cleats come in an array of options, giving a choice of:

- surface area (width and size of the pedal body and cleat)

- rotational freedom around the Z axis of the pedal (known as "float")

- distance from the pedal axis to the bottom of the cleat ("stack height")

- total mass of cleat and pedal

- material construction (carbon, alloy, titanium, thermoplastic etc.) which largely governs total mass

- pedal axle length

To the consumer, the main preferred characteristics are reduced weight and an increased surface area. A decrease the mass of the pedal, is only in the order of ~100g between high and low end models, approximately 0.01% of the total mass of a standard racing bicycle. An increase in the contact patch with the pedal is achieved by widening and lengthening the cleat within the constraints of the 2-4 bolt mounting points, and increasing the surface area of the top of the pedal. This serves to distribute the pressure more evenly on the sole of the foot. Smaller contact patches can lead to pressure pain, Morton’s neuroma, or a "hot spot" on the sole of the foot, commonly seen with mountain bike pedals and cleats that require a smaller cleat for optimal mud shedding (Davis et al., 2011; Silberman et al., 2005).

1.9 A step backwards

Little research has been conducted on the bicycle pedal and its ideal construction (Cruz & Bankoff, 2011;Boyd et al., 1997;Gregersen et al., 2006;Gregor & Wheeler, 1994;Mornieux et al., 2008). The modern day market for pedals and their manufacturers has grown, but without a concurrent increase in knowledge about how to optimally position the foot. A lower stack height should allow the foot to follow a more circular path during the pedal stroke, and some models of pedal have sought to address this by aligning the foot with the pedal axis (Koninckx et al., 2008).

This Vista Magic X pedal is similar to the non clipless Shimano DynaDrive pedal (Shimano, Japan), but the zero stack height comes at the expense of an increased pedal axle length.

There has been a significant gap in the scientific research conducted into cycling - namely that studies focus on adjustments to the bicycle in the sagittal plane only. Ergonomic changes along the frontal plane have not been previously explored. This is especially important at the pedal where the cleat and pedal interface can be altered along all three axes. To date there has been little to no research conducted into how positioning the foot laterally and manipulating the rotational freedom of the pedal can affect performance, comfort and/or injury prevention.

Previous research on pedals is outdated (Boyd et al., 1997) and used pedals with large stack heights and non-modern systems of retaining the foot such as clips and straps rather than an automatic release. The range of movement was limited, in contrast to some modern pedals which can allow up to 20deg of rotational movement before disengaging (Speedplay, USA). Modern shoe construction is governed entirely by pedal and cleat system attachments and as such any new research should take into account these technological differences, which is lacking in the current literature.

1.10 Q Factor

The position of the feet along the frontal plane even has a designated term in cycling, and is known as "tread", or more commonly "Q Factor". Q Factor is defined by the distance between the feet along the frontal plane, taken from the outside edge of each crankarm where the pedal is to be inserted and measured in mm.

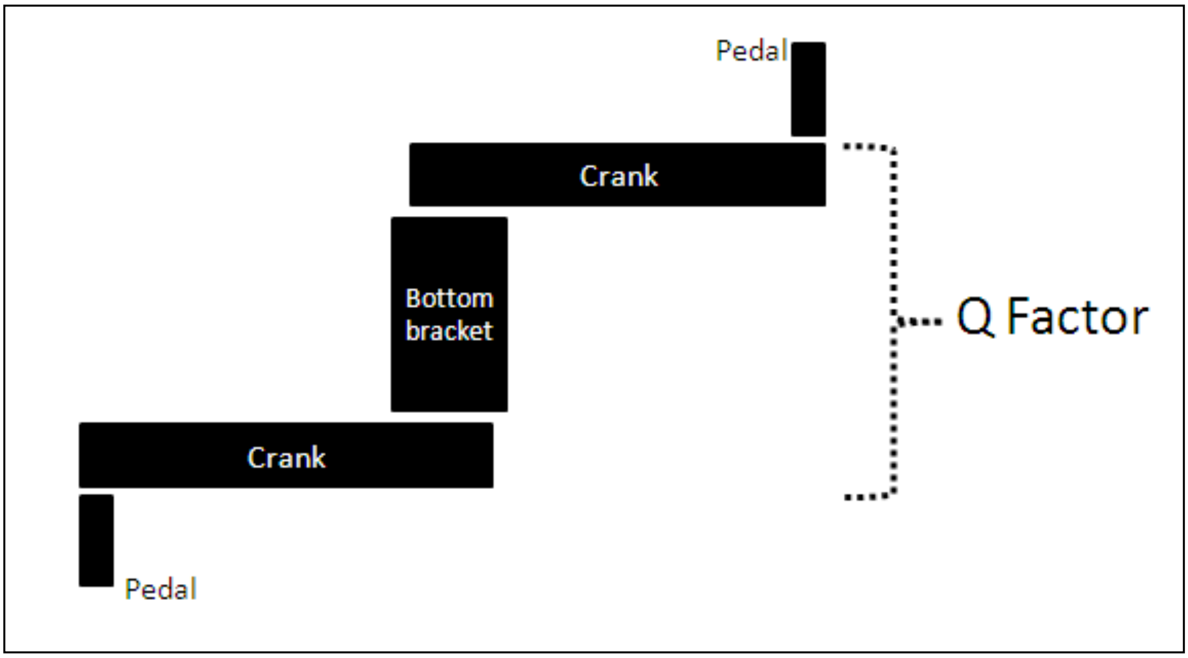

Figure 12. The measurement of Q Factor.

A term originally devised by Grant Petersen of Bridgestone Bicycles (USA), "Q Factor" is short for "Quack Factor", given that a large distance between the feet, or a high Q Factor, will cause the cyclist to pedal as if they were a duck waddling! This rather tongue in cheek nomenclature has been readily adopted by the bicycle industry, and manufacturers will even stamp "Q Factor" directly onto components as well as providing information in datasheet specifications as to the Q Factor of a component. Some pedal manufacturers such as Time Sport International and Look claim that reduced Q Factor can be obtained by using different cleats or changing pedal axle length - this is not strictly Q Factor but an additional governance of foot location.

The use of Q Factor in order to improve the recruitment of cycling muscles and subsequently boosting force effectiveness at the pedal, could be a method of improving cycling performance. It is known that in weighted squat exercise, changing the foot placement laterally (stance width) can result in a change in muscular activation (Escamilla et al., 2001;McCaw & Melrose 1999).

Knowing that the quadriceps group is responsible for the majority of the force production during the downstroke of the pedal cycle, Q Factor adjustment could be made in order to optimise the recruitment of these muscles and therefore performance. A particularly high Q Factor for example (placing the feet further apart), may cause a lengthening of the vastus medialis and decreased force capability, whereas a Q Factor too low could cause a similar effect in the vastus lateralis, as well as creating tension at the stabilising tensor fasciae latae, and subsequently the knee.

Even though most crank arm manufacturers provide information on Q Factor, and some pedal manufacturers allow greater lateral adjustment of the foot through pedal axle length and pedal/cleat design, there is no empirical data to inform the end user of the optimal Q Factor for their given application.

Q Factor is set by the crankarms, and generally limited by bottom bracket width, tyre clearance with the bicycle and crankarm size. For this reason a typical Q Factor will differ between cycling disciplines rather than between rider sizes: in track cycling where less clearance is needed due to the single chainring mounted on the crank a lower Q Factor (~144mm) is found. Road cycling requires two or three chainrings to be mounted on the crank, and therefore more clearance and a longer bottom bracket axle increases the Q Factor to around 150mm. Mountain biking and touring both use three chainrings as well as wider set chainstays and larger tyres, and for this reason the Q Factor on a mountain bicycle can approach 180mm for some makes of cranks. Given the attention that is sometimes paid to crankarm length by amateur and professional cyclists (typical range 165-180mm), the almost complete disregard for an optimisation in Q Factor over a much wider range (144-180mm) seems illogical.

1.11 A performance enhancer

As well as the optimisation of muscular recruitment, another possible benefit would be improved aerodynamics - as mentioned previously aerodynamic drag is the largest resistive force acting on a cyclist, and especially in a timed event such as the bike leg of a multisport race, or an individual or team time trial on the road or track, a narrower Q Factor could potentially improve aerodynamics by reducing the frontal area of the cyclist.

In 1996, for the Atlanta Olympics, extra funding was given to the American cycling team in order to improve their chances to win medals at a home Games (Blangger 1996). Cycling was targeted (especially track cycling) due to the largely predictable nature of the events, where a reduction in aerodynamic drag of the bicycle and rider would result in faster times and greater medal potential, but requiring investment into research and engineering. A group of engineers, working on what was dubbed "Project '96", used US Air Force wind tunnel facilities in order to optimise the shape of the bicycle and the airflow over the bicycle and rider (Parker 1994). One area that was explored was the effect of varying the distance of the riders legs to the bicycle frame, which would be the result of a narrower Q Factor. Aerodynamics in this situation were improved as legs were moved closer to the frame (up to 1 inch away from the bicycle). A narrow bicycle itself could also be made more aerodynamic as a reduction in bottom bracket shell width, required to lower Q Factor, in turn reduces the frontal area of the bicycle and therefore decreases aerodynamic drag. Trek found that their custom narrow bicycle was more aerodynamic in the wind tunnel than the standard version (Coyle, 2005).

1.12 Armstrong's secrets

Within professional cycle sport, Q Factor has only fairly recently been explored as a potential performance enhancer. In the early 2000s at the Tour de France, always a hotbed for cycling innovation, the American cyclist Lance Armstrong sought to emulate the exceptional time trialling ability of his rival Jan Ullrich from Germany (Armstrong 2004), who possessed a custom built bicycle with a narrow Q Factor. Constructed by Andy Walser, a Swiss bicycle manufacturer with a keen interest in biomechanics (www.walser-cycles.ch), Ullrich's bicycle was built with a special narrow bottom bracket shell and reduced clearance for the rear wheel. A custom bottom bracket axle and crankarms allowed for the normal double chainring but with a highly reduced Q Factor of <130mm. Armstrong instructed his bicycle manufacturer (Trek, USA) to first obtain a Walser bicycle (purchased individually by an employee of the company to avoid suspicion!) and then copy and refine the design for his own personal use. The engineers at Trek were able to reduce the Q Factor to approximately ~128mm again using custom components, and Armstrong tested the new bicycle in a short stage race competition and a training camp in Lanzarote (Coyle 2005). Unfortunately, Armstrong merely chose to reduce his Q Factor to match that of Ullrich's, a taller, heavier rider who used a lower cadence compared with the fast pedalling, smaller Armstrong. Armstrong did not prefer this lower Q Factor, and felt that his power output over a long distance was affected, albeit without conducting any rigorous testing. The narrow bicycle was shelved, with a reported investment of nearly $250,000 (Coyle, 2005) and instead given to a team mate of Armstrong's, Viatcheslav Ekimov , who went on to use it to win the gold medal at the 2004 Athens Olympics in the individual road time trial.

1.13 Q Factor to win

Other cyclists apart from Armstrong and Ullrich (who was a Tour de France and Olympic champion) have used custom narrow bicycles at the highest level of cycle sport in an attempt to improve their performance: former world time trial champion Hanka Kupfernagel, former Olympic and world champion Nicole Cooke, Commonwealth Games medallist and Tour de France points jersey winner Baden Cooke, Olympic medallist and American champion Levi Leipheimer, world medallist and German champion Michael Rich, along with other professional and also amateur cyclists. Most riders of narrow bicycles (such as Armstrong and Ullrich) were using <130mm Q Factors, which was preferred by Ullrich but not by Armstrong. Conversely, Armstrong's teammate Viatcheslav Ekimov found the <130mm Q Factor much more comfortable and rode the narrow Trek bicycle until his retirement in 2006.

It is highly likely that the optimal Q Factor, like crankarm length, handlebar and saddle position is an individual variable that should be adjusted to suit the cyclist. Some successful cyclists have used a low Q Factor to improve their performance, however there is also likely to be a limit on how narrow the feet can be placed before performance decreases.

1.14 From cycling to walking

Cycling occurs within a relatively fixed predetermined space. Walking is a movement with free range of motion, and altering step width whilst walking has been found to change the oxygen cost (Donelan et al., 2001) and therefore efficiency, of the movement.. By increasing the step width beyond that of self selected, more oxygen is consumed and the action becomes less efficient. During cycling, the cyclist has no way of altering their Q Factor, and cannot explore their degrees of freedom to ensure that they are pedalling efficiently.

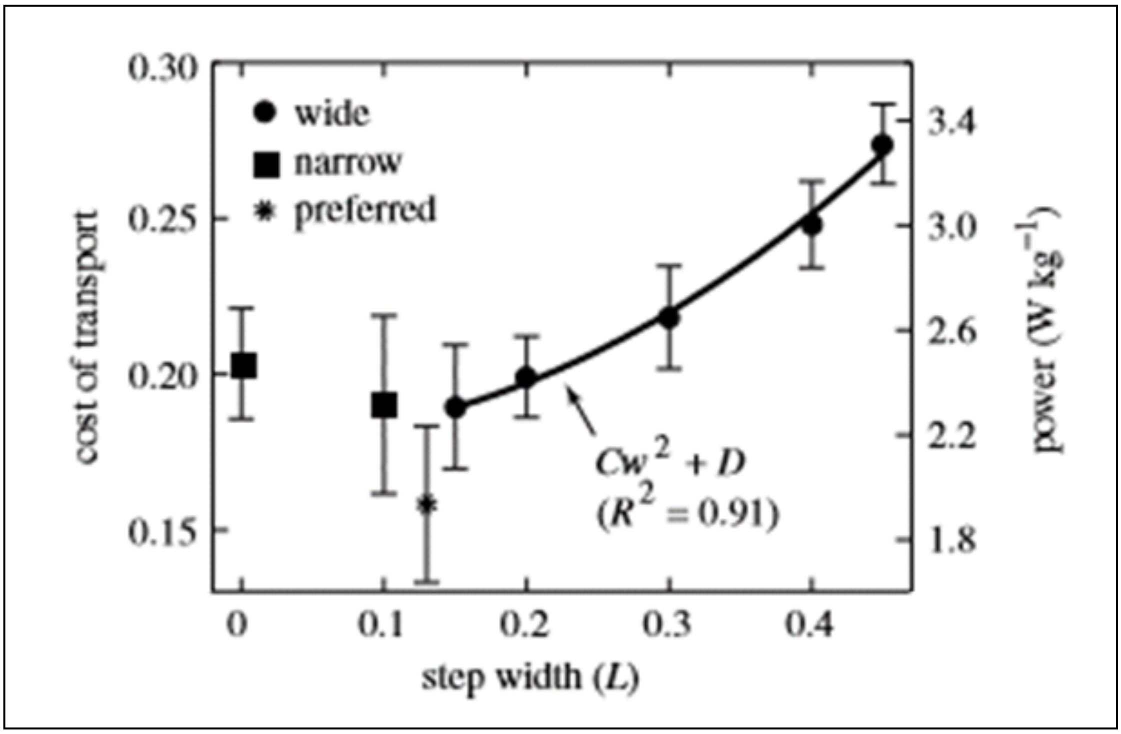

Figure 13. Oxygen cost at a reduced step width (from Donelan et al., 2001).

The self selected and most economical step width whilst walking is 100-130mm (Donelan et al., 2001), which is lower than typical Q Factors found on road and mountain bicycles (150mm+). It is possible that by reducing the Q Factor on a bicycle to that approaching this lower width, the oxygen cost of cycling can be decreased as major cycling muscles as described above could be recruited and activated in a manner even more similar to walking than a typical cycling activation profile.

It thus remains to be explored how Q Factor and foot positioning can be optimised on the bicycle to provide improved efficiency and kinematics. It should always be borne in mind that although cycling is a discrete activity, it found its genesis in the action of walking, and it is by making use of the body's evolution to walk and run that we can find our optimal position.

1.15 Aims

The manipulation of Q Factor has the potential to provide greater efficiency and a recruitment pattern of muscular activation that is closer to that of walking. In this thesis I aim to explore how altering Q Factor and foot location whilst cycling can affect muscular activation, kinematics and mechanical efficiency during cycling.

The effect of manipulating Q Factor upon gross mechanical efficiency, muscular activation and time trial performance will be analysed, in order to understand whether lower Q Factors that approach those of step width during gait improve performance and muscular recruitment. Then self selection of foot positioning will be explored and how it affects these physiological markers, and the relationship with kinematic instability whilst cycling.

1.16 Methodological approaches

In order to explore gross mechanical efficiency, muscular activation, kinematics and performance variables a range of techniques must be used.

Measurements of gross mechanical efficiency (GME) are conducted using expired gas from an exercising individual. GME is distinct from delta efficiency (DE) as it represents the entire result of all metabolic processes and the relationship to external work, rather than DE which is an incremental ratio measure (Ettema & Loras, 2011; Castronovo et al., 2013). DE has been shown to be more variable than GME (Moseley & Jeukendrup, 2001; Moseley et al., 2004) and analysis of GME requires only a single bout of exercise (Lucia et al., 2004), compared with the DE which requires multiple bouts of exercise and the slope of the regression line taken (Francescato et al., 1995), allowing for efficient use of the method in the laboratory. GME has also been shown to be relatively immune to circadian rhythm effects (Noordhof et al., 2010). Nevertheless, in order to achieve a high level of precision and repeatability, great care must be taken when performing gas analysis for efficiency calculations, such as the careful calibration of equipment and the use of Douglas bags instead of online gas systems (Hopker et al., 2011), as well as calibrated and recognised devices for measuring external work whilst cycling, such as a Monark ergometer, SRM cranks or hub based Powertap power meter (Bertucci et al., 2005; Paton & Hopkins 2001; Peiffer & Losco 2011). It is vital that the work performed and pedalling cadence utilised for the purpose of evaluating GME should be submaximal and steady state, which serves both to allow correct measurement of GME and to reduce fatigue effects. Ensuring that respiratory exchange ratio (RER) remains below 1.0 (and excluding any data where RER increases above 1.0) will therefore further aid the precision of the measurement (Hopker et al., 2011).

Muscular activation can be recorded either through surface electromyography (sEMG), where electrodes are placed upon the skin to detect electrical activity of the muscle below it, or through wire inserts into the muscle itself (Hug & Dorel, 2009; Raez et al., 2006). For volunteer subjects performing exercise, surface EMG is many times more preferable and efficient for use in research. In order to isolate the specific muscles to be analysed, guidelines are available as to best sensor placement practice, focusing on the main body of the muscle to minimise the recording of activity from nearby muscles (Hermens et al., 2000). Raw signal data must be processed before use, and appropriate techniques for normalisation and root mean square (RMS) time periods (eg. <50ms for cycling activity) should be used. Some research has used a maximal voluntary contraction (MVC) of a muscle for normalisation whilst cycling, however this procedure can provide significant error and variability, and instead a dynamic method is preferable (Albertus-Kajee et al., 2010; Hug & Dorel, 2009).

Kinematic measurements can be conducted either through video recording (Bailey et al., 2003; Lage et al., 1995; Neptune & Hull 1999) or infrared analysis such as a Vicon system (Besier et al., 2003; O'Neill et al., 2011; Shan, 2008). A multi-camera (>3) infrared system allows for the placement of markers in locations that may not be seen by a 2 camera high speed video system, and the integration of many infra red cameras (ie. >10) is more practical for data analysis than multiple high speed video systems. Best practice will involve the use of photographs and marked areas on repeat trials to ensure consistent marker placement, and reduce any additional error alongside that experienced by soft tissue artifacts (Leardini et al., 2005)

1.17 References

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2 THE EFFECT OF Q FACTOR ON GROSS MECHANICAL EFFICIENCY AND MUSCULAR ACTIVATION IN CYCLING

This study was conducted in order to explore the effect of using two standard Q Factors (150 and 180mm) alongside two narrower Q Factors (90 and 120mm) on both gross mechanical efficiency and muscular activation. The hypothesis was that narrower Q Factors would result in reduced activation of major cycling muscles and therefore improve (lower) oxygen consumption at a given submaximal workload. Trained cyclists were used for this study to ensure that the participants largely had a consistent pedalling action. For the measurement of gross mechanical efficiency, an important aspect in determining cycling performance, submaximal workloads were used.

This chapter has been published in the Scandinavian Journal of Medicine and Science in Sports, on May 21, 2012:

Disley, B.X., Li, F.-X., 2012. The effect of Q Factor on gross mechanical efficiency and muscular activation in cycling. Scandinavian Journal of Medicine and Science in Sports (May 21)

2.1 Introduction

Correct bicycle fitting is an essential aspect of cycling performance, injury prevention and comfort. The bicycle needs to be adjusted to the biomechanical characteristics of the rider in order to allow the rider to pedal efficiently. One aspect of bicycle fitting that has received no scientific attention, to date, is the “Q Factor” of a bicycle.

Grant Petersen (Bridgestone Bicycles, USA) popularised the term Q Factor in the 1990s (previously known as “tread”) to describe the horizontal width between pedals, measured from the outside face of the crankarm where the pedal is inserted, to the corresponding outside face on the opposite crank when it is positioned in the same plane. Bicycle manufacturers use the term Q Factor in marketing documents and even stamped upon cranks themselves (e.g. Campagnolo, Italy). The Q Factor of a crankset, along with the position of the cleats attaching the shoes to the pedals, determines where the foot is laterally positioned throughout the pedal stroke.

Currently no mass-produced bicycle has a Q Factor lower than 135mm: a typical Q Factor ranges typically from ~150mm for a road bicycle, up to ~180mm for a mountain bicycle. Wider Q Factors for mountain bicycles are largely due to a triple chainring system at the bottom bracket, which limits minimum Q Factor due to clearance issues with the frame. Modern bottom bracket systems (such as BB30) permit narrower Q Factors <150 mm by housing the bearings within the frame, coupled with compatible crank systems. However, many bicycles would be able to accept Q Factors lower than 150 mm without limitations on clearance. Some Olympic and World Champion cyclists have successfully used custom bicycles equipped with a low Q-Factor (e.g. <130mm) in order to improve performance, winning Olympic and World Championship medals and time trial stages of the Tour de

France. One rationale for this strategy is that the recruitment and activation of major cycling muscles will be improved with a reduction in Q Factor as stance width approaches that of bipedal walking and therefore result in a more effective delivery of power to the bicycle.

In spite of such attempts, to date, there have been no scientific studies performed upon the effect of narrowing the pedal stance of a bicycle on physiological and biomechanical variables.

Previous research in cycling where componentry aspects of the bicycle have been altered, such as seat height and handlebar position, have been shown to negatively affect parameters such as oxygen cost (Grappe, 1998; Peveler, 2008), electromyography (EMG) activity (Mileva & Turner, 2003; Sanderson & Amoroso, 2009) and power output (Mandroukas, 1990; Martin & Spirdoso, 2001; Peveler et al., 2007; Too & Landwer, 2000) in cyclists, when the position of the cyclist has been changed from the optimum.

It is known that altering stance width has an effect upon joint moments and electromyography (EMG) activity during weighted squat exercise (Escamilla et al., 2001; McCaw & Melrose, 1999; Paoli et al., 2009). However, no studies have explored the effect of changing stance width on a constant cyclical lower body movement involving relatively low forces. By bringing the lower limbs closer to the vertical (median) plane of the bicycle (ie. by reducing the Q Factor), it is possible that muscles will be recruited in a manner more similar to walking. Donelan et. al (2001) found that the metabolic cost of walking was decreased at lower step widths, compared with wider step widths where the shank angle will be decreased from vertical at the commencement of knee/hip extension in the gait cycle.

The aim of this study was to determine whether narrowing the Q Factor had a beneficial effect upon efficiency and muscular activation.

It was hypothesized that narrowing Q Factor would result in a lower oxygen consumption (as found in human walking) for a given power output and therefore increased gross mechanical efficiency (GME), and that the level of muscular activation of major muscles involved in the cycling action would decrease as Q Factor is reduced.

2.2 Methods

2.2.1 Subjects

Twenty-four trained cyclists (11 male: VO_{2max} 60.7 ± 6.8ml.kg.min^{-1}, peak power output (PPO) 363 ± 44 W, mass 77.3 ± 6.1kg, height 182.7 ± 5.5cm, age 23.7 ± 6.0 yrs ; 13 female: VO_{2max} 54.8 ± 4.1 ml.kg.min^{-1}, PPO 262 ± 25 W, mass 63.4 ± 4.3, height 168.2 ± 4.8cm, age 28.7 ± 10.9) volunteered for the study and gave informed consent for the study, which was approved by the University ethics committee. All subjects had a history of competitive cycling for >1yr, and were accustomed to maximal exercise.

2.2.2 Setup

All tests were performed upon a fully adjustable custom static bicycle, equipped with a torque sensor in the rear hub to measure power output (Powertap, Saris, USA), and mounted upon an electromagnetically braked turbo trainer to provide resistance (Tacx i-Magic, Tacx, The Netherlands) (Figure 15). The custom bicycle consisted of two adjustable shafts allowing for manipulation of saddle and handlebar position, mounted upon an enclosed box section, housing a chainring and reed switches in order to determine crank position during the pedal cycle. A proprietary crank system that allowed manipulation of Q Factor was used, consisting of aluminium crank arms mounted upon removable bottom bracket axles of differing lengths, permitting a range of Q Factors from 90 mm upwards.

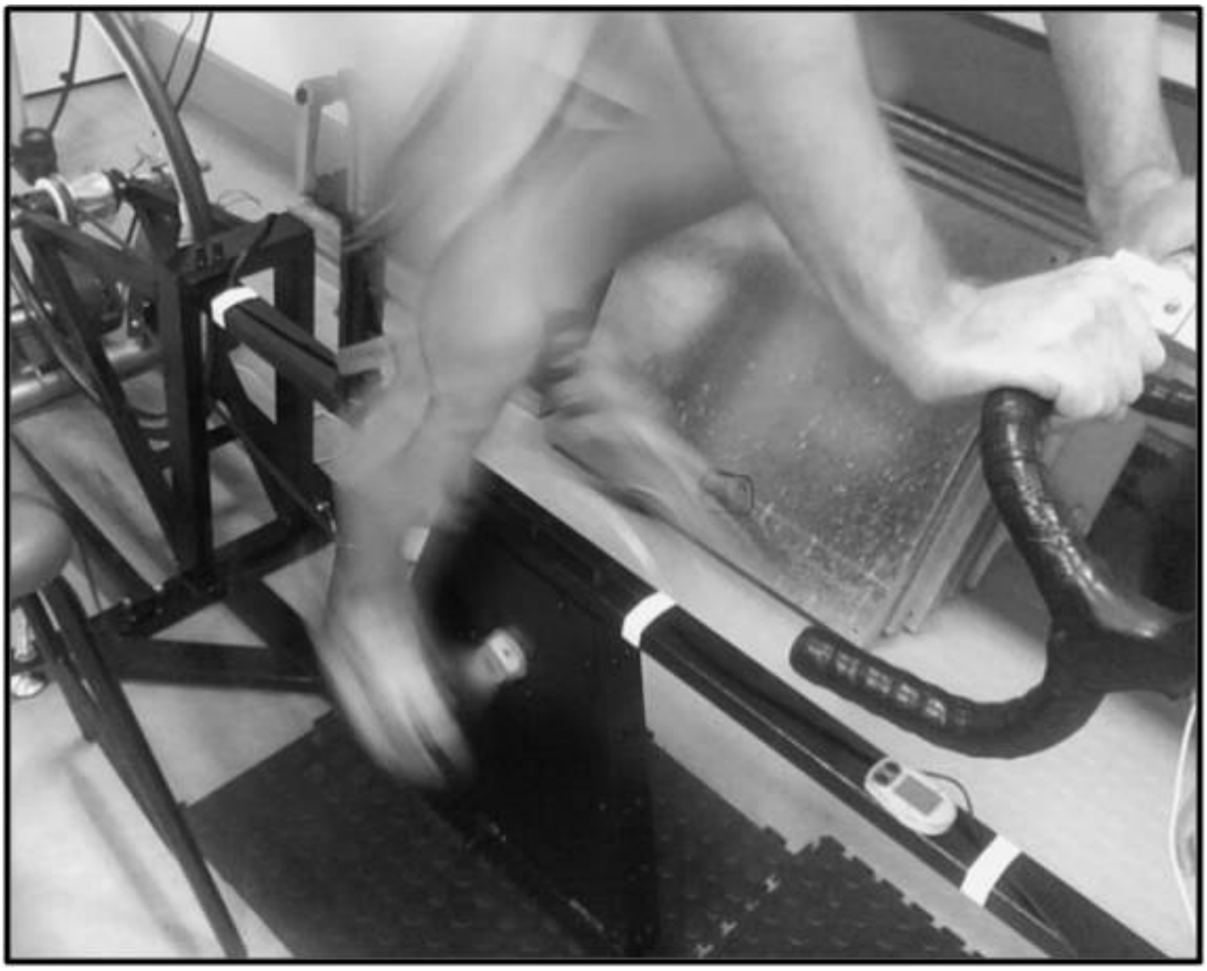

Figure 14. Static ergometer with enclosed chainring system.

The Powertap was statically calibrated with weights of known mass to ensure its accuracy, and is comparable to the SRM system in its accuracy (Gardner et al., 2004). Saddle height and handlebar position were self selected and recorded and the subjects own pedals and clipless shoes used. Saddle height and handlebar position was kept constant throughout the experiment.

Participants were instrumented with surface EMG sensors and data collected using Spike software (CED, United Kingdom). Sensor locations were set using Seniam guidelines for sensor placement (seniam.org), and mounted upon the vastus lateralis (VL), vastus medialis

(VM), tibialis anterior (TA) and gastrocnemius medialis (GM), as major muscles involved in the cycling action (Hug & Dorel, 2009). Skin was first shaved and then cleaned using an alcoholic solution, and conductive gel used in order to provide adequate contact between the electrodes and the skin. Heart rate (HR) was measured throughout using a chest belt transmitter (Saris, USA).

2.2.3 Experimental protocol

Subjects were required to visit the laboratory on two occasions. The first involved an incremental exercise test to exhaustion, in order to determine VO_{2max} and PPO. Q Factor was set for this test at 150mm (Q150), similar to a standard road bicycle. Subjects starting pedalling at either 100 W (female) or 200 W (male), at a self selected cadence, and resistance was increased by 30 W every 3min, until the subject reached volitional exhaustion or cadence dropped below 60rpm. Expired gas was collected for 60sec at the end of each 3min stage using Douglas bags; VO_{2max} was determined as the peak 60sec during the final stage and PPO was calculated as the highest 60sec average power during the final stage. Heart rate (HR) was measured throughout using a chest belt transmitter (Saris, USA).

The second session was performed >48hr after the incremental test. After a warm up period of 5min at <150 W, a dynamic normalization trial of 3min at a power output corresponding to 60% PPO in order to achieve a submaximal steady state for the purpose of evaluating GME, using Q150 and cadence of 60rpm was conducted, for the purpose of EMG analysis (Albertus-Kajee et al., 2010). The session consisted, for each Q Factor (Q90, Q120, Q150 and Q180), of 2 stages 5min in duration at 60% PPO and 90rpm. The order of experimental conditions was randomized across subjects and all stages were separated by 3min rest. Subjects were required to remain seated during the 5min stages and to keep their hands placed on the horizontal section of the handlebar.

2.2.4 Measurements and analysis

120sec of expired gas, starting and finishing on an exhaled breath, was collected using Douglas bags at the end of each 5min submaximal stage, during the second session, for the purpose of determining GME. The need for careful calibration of equipment and handling of gas samples for accurate results has been previously described by Hopker et al. (2011). In order to minimize potential effects of diffusion, immediately prior to testing all Douglas bags were evacuated of their residual volume, and a dry gas meter employed to determine that no further residual gas could be extracted. All tests were performed using the same gas analyser (Servomex, UK), which was calibrated using three separate gas mixtures of known concentration, in order to determine linearity and accuracy. During analysis, the gas analyser was recalibrated after every four bags and 0.125 l of gas was removed from each. A ~120sec sampling period ensured that large gas volumes of <100 l were collected, in an effort to reduce the effect of minor but potentially contaminatory gases that may be present in evacuated Douglas bags, as well as any residual volume present, as these are the largest sources of error in Douglas bag measurement (Hopker et al., 2011).

GME was calculated using the ratio of work accomplished in kcal.min^{-1} to energy expended in kcal.min^{-1} during the final 120sec of each stage following the method of Lucia et al. (2004), using the ratio of work accomplished to energy expended per minute. Work accomplished was calculated from the power output recorded by the Powertap converted to kcal.min^{-1}. Energy expended in kcal.min^{-1} was calculated using the energy equivalent for VO_2 based upon RER. GME was determined as the average of the two stages for each Q Factor.

EMG activity was recorded at 1000Hz. Root mean square (RMS) activity for each muscle was calculated over a period of 30 complete pedal cycles over 20ms, during the third minute of each stage, and a second order low pass Butterworth filter applied with cutoff frequency of

10Hz. Level of EMG activity for each muscle was calculated as a percentage of the normalization period. In addition the peak RMS activity for each muscle during each individual pedal stroke was calculated, in order to provide timing of peak activation (PEAK) onset of activation (ON, >25% peak RMS) and offset of activation (OFF, <25% peak RMS) (Hug & Dorel, 2009).

The angle of activation for PEAK, ON and OFF was determined using reed switches placed every 45^{o} around the face of the crank synchronized with the EMG data, and constant velocity was assumed during each 45^{o} segment.

A repeated measures ANOVA was used in order to determine overall differences in GME, average RMS, PEAK, ON and OFF for each Q Factor. If the laws of sphericity were violated then the Greenhouse-Geisser correction was used. Where appropriate, post hoc testing was conducted using Fisher's LSD.

2.3 Results

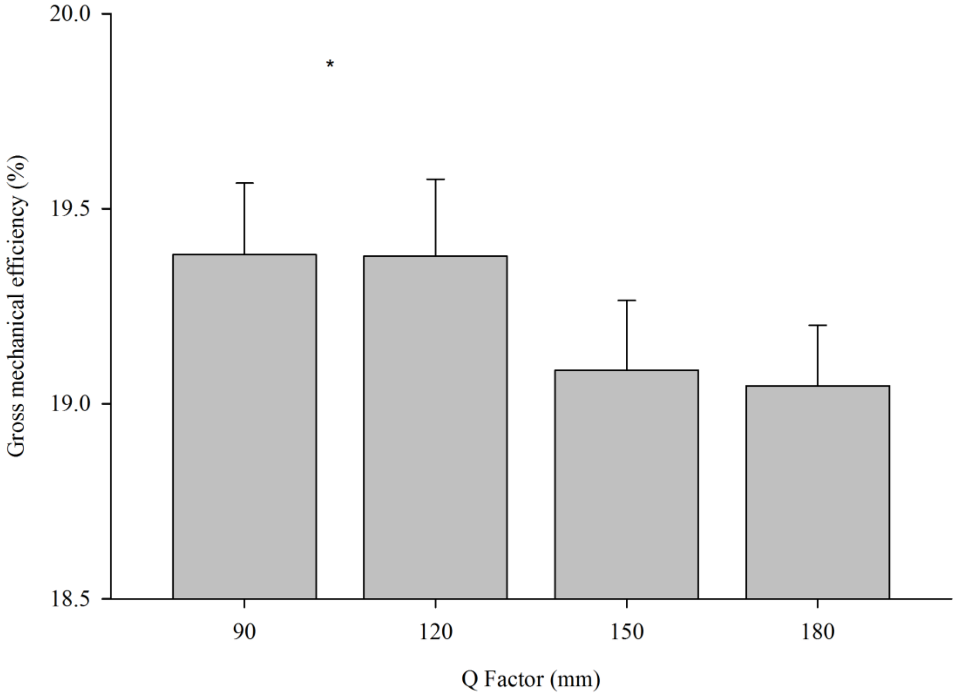

Figure 15. Changes in gross mechanical efficiency GME with different Q Factors. *GME for Q90 and Q120 is higher (19.38% and 19.38%) than Q150 and Q180 (19.09% and 19.05% $P < 0.006$). Error bars represent SE.

Altering Q Factor on a bicycle results in a change in GME ($F(1,2.699)=7.423$, $p<0.001$, $\eta^2=0.244$). Post hoc analysis revealed that Q90 (19.38±0.90%) was significantly higher than Q150 and Q180 (19.09±0.87% and 19.05±0.76%, p<.006), and that Q120 (19.38±0.97%) was significantly higher than Q150 and Q180 (p<.006). There was no significant difference between Q90 and Q120, nor was there a difference between Q150 and Q180. In addition, gender did not have an effect upon GME ($F(1,2.645)=0.540$, $p=.635$). All participants remained in steady state (RER <1.0) during the submaximal 60% PPO workload.

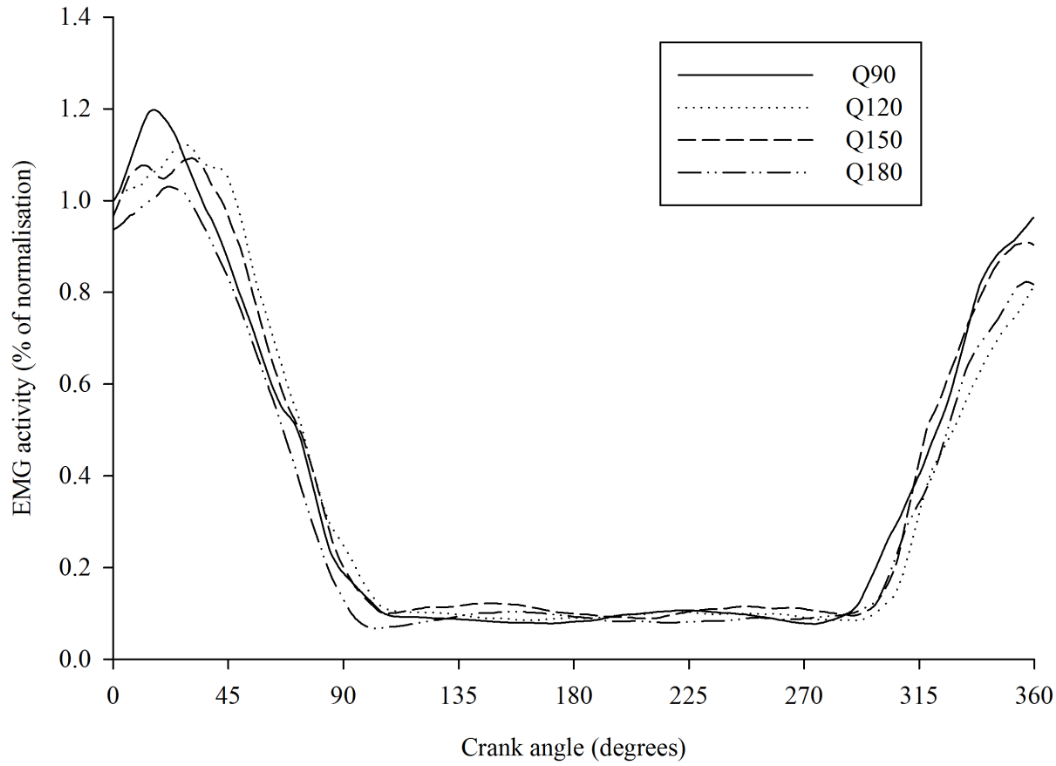

Figure 16. EMG activity of the vastus lateralis for a single participant as a function of crank angle.

There were no significant differences found between Q Factors at timing of onset of muscular activation, peak activation and offset of activation (see Table 1.). In addition, the level of muscular activation, calculated as a percentage of activation during the normalization trial, was not significantly different between Q Factors. There was a trend towards a change in ON for the GM and VL (p=.076 and p=.064), but not PEAK or OFF for the GM and VL. Muscles were recruited at the same point during the pedal stroke and with the same level of activity, irrespective of the Q Factor used, even though a change was found in GME.

	Q90	Q120	Q150	Q180	Result of repeated measures ANOVA
GM Onset (deg)	117 ± 49	124 ± 42	110 ± 53	105 ± 57	F=2.732, p=.076
GM Peak (deg)	141 ± 54	150 ± 42	140 ± 56	131 ± 57	F=1.433, p=.248
GM Offset (deg)	172 ± 57	184 ± 48	175 ± 61	162 ± 59	F=1.686, p=.191
TA Onset (deg)	335 ± 37	326 ± 44	315 ± 32	325 ± 55	F=1.138, p=.338
TA Peak (deg)	3 ± 36	359 ± 44	345 ± 30	357 ± 51	F=1.315, p=.281
TA Offset (deg)	36 ± 37	38 ± 52	15 ± 37	30 ± 63	F=1.163, p=.333
VM Onset (deg)	19 ± 36	26 ± 34	9 ± 44	31 ± 49	F=1.483, p=.229
VM Peak (deg)	54 ± 34	56 ± 31	43 ± 39	57 ± 48	F=0.958, p=.419
VM Offset (deg)	83 ± 40	86 ± 42	73 ± 43	88 ± 54	F=0.959, p=.402
VL Onset (deg)	20 ± 32	1 ± 21	24 ± 30	12 ± 37	F=2.589, p=.064
VL Peak (deg)	33 ± 56	30 ± 25	52 ± 32	39 ± 36	F=1.042, p=.367
VL Offset (deg)	77 ± 42	61 ± 26	79 ± 41	71 ± 40	F=1.803, p=.159

Table 1. Timing of muscular activation for the GM, TA, VM and VL at Q90, Q120, Q150 and Q180 (Mean ± SD, n=20). 0deg represents a vertical crankarm/top dead centre.

	Q90	Q120	Q150	Q180	Result of repeated measures ANOVA
GM Level (%)	229 ± 105	252 ± 129	213 ± 91	219 ± 86	F=1.724, p=.189
TA Level (%)	240 ± 137	217 ± 132	192 ± 57	230 ± 107	F=0.641, p=.549
VM Level (%)	206 ± 133	161 ± 95	184 ± 116	180 ± 145	F=0.697, p=.559
VL Level (%)	114 ± 29	116 ± 40	115 ± 20	108 ± 15	F=1.770 ,p=.177

Table 2. Level of activation for the GM, TA, VM and VL at Q90, Q120, Q150 and Q180 (Mean ± SD, n=20)

2.4 Discussion

2.4.1 Key findings

The aim of this study was to explore the effect of Q Factor on cycling efficiency and muscular activation. A reduction in Q Factor resulted in an increase in GME. However, level and timing of muscular activation was unchanged in the GM, TA, VM and VL.

2.4.2 Gross mechanical efficiency

The data show that the narrower Q Factors Q90 and Q120 result in higher GME (~0.3%) than the wider Q Factors Q150 and Q180. This is the first time that Q Factor has been scientifically studied, and the data show that lateral positioning of the foot has an effect upon cycling efficiency (1.5-2% increase in power output) compared with previous research examining anterior/posterior positioning, when correctly examined (van Sickle & Hull, 2007; Mandroukas, 1990).

An increase in GME of 0.3% represents an improvement in power output at submaximal levels of approximately 1.5-2.0%. Professional cycling stage races such as the Tour de France often require athletes to work submaximally for long periods of time (4-6hrs), as the effect of drafting in a large group reduces overall workload to submaximal aerobic intensity. In such a circumstance this reduction in energy turnover represents a worthwhile gain, given that the margin of victory for 3 week stage races is often in the region of a few minutes rather than hours (Jeukendrup et al., 2000). In an event such as a long distance triathlon with a 180km non drafting bike section, athletes will be working close to the submaximal level studied (Laursen et. al 2002). At a constant power output of 180-280 W, this relates to approximately 3-5w saved, or 2-3min over the course of the cycle.

In this study athletes were exposed to different Q Factors but only for 5min periods. We have shown that an acute exposure to a reduction in Q Factor results in an increase in GME, however there may be a training effect that could allow an even greater increase in GME than that displayed here.

2.4.3 Level and timing of EMG activity

There was no difference in either the level of activation or the timing of activation of the major cycling muscles measured (GM, TA, VM and VL). Given that the cyclists in the present study were all trained cyclists, the change in foot placement (a range of 45mm each side) may not have been sufficient to cause a change in muscular activation from their normal pedalling action. With an acute exposure to a different Q Factor, firing of the motor neurons may not have been sufficiently different for the level and timing of EMG activity to change. The instrumented ergometer allowed for analysis of timing of EMG activity during the pedal stroke, yet there were no significant differences between the Q Factors. There was, however, a trend towards a change in the angle of onset of activation for both GM and VL, and it is possible that this, along with other factors such as the behavior of other muscles than those analysed, may combine to produce the change in GME found.

Few studies have related changes in EMG activity of the muscles to mechanical efficiency, often focusing purely on oxygen consumption and cycling economy (e.g. van Sickle & Hull, 2007). It is possible that other muscles involved in the cycling action are responsible for the increase in GME at lower Q Factors, however as the increase in GME was small, the signal-to-noise ratio inherent in the use of EMG may prevent the detection of slight changes in muscular activity in the muscles measured.

During testing 23 of the 24 participants reported a dislike of Q180, and that the pedaling action felt “odd” or “uncomfortable”, preferring instead to pedal with Q90 or Q120. This non-localised discomfort implies a potential muscular recruitment discrepancy, but probably detrimental only for the wider Q Factor of 180mm. Future work could involve determining levels of comfort and their effects over longer durations than those explored in the current study. Increasing the Q Factor above 180mm may result in detectable changes in EMG activity, but reducing the Q Factor below 90mm is impractical for bicycle manufacturers due to a mechanical limit in the minimum width of a bottom bracket and crank set. Further muscles involved in hip adduction and abduction of both legs could also be explored - due to restrictions in equipment capability, only four muscles of the right leg were analysed in this study.

2.4.4 Mechanical considerations

Further research is required to explore the force application at the pedal itself in order to fully determine the source of the increase in GME. By moving the pedals closer to the centerline of the bicycle, a more efficient transfer of force to the pedal, with less ineffective tangential force or medio-lateral component during the pedal stroke (Bini et al., 2013), would result in a higher measured power output for the same level of oxygen consumption, thereby increasing GME. If indeed there is no change in timing or level of activation of the major cycling muscles when Q Factor is manipulated, optimal force application could favor lower Q Factors during cycling. Future study should make use of instrumented pedals in order to determine whether this hypothesis is correct.

2.4.5 Perspectives

In the world of cycling and triathlon, technology is becoming more important for increases in performance. At submaximal intensity efficiency with lower Q Factors is increased, yet further study is required to determine the effect of manipulation on Q Factor during maximal aerobic and anaerobic intensity performance. Nevertheless, the improvement in cycling efficiency with a narrower Q Factor could be realized with the advancement of modern bicycle construction, along with the potential for further benefits (such as better aerodynamics or injury prevention).

2.5 Acknowledgments

We would like to thank Bob Tobin of Cyclepowermeters Ltd for his assistance with equipment, and Philippa Blandford and Ella Hopkins for their support with data collection.

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3 SELF SELECTED FOOT POSITIONING IN CYCLING

Having determined that narrower Q Factors are more efficient for submaximal workloads, this study was devised in order to explore how cyclists would self select their foot position (both in terms of float/pedal angles and also Q Factor) and how this related to optimal. A wider range of participants were used of both genders, from recreational cyclists to European Masters champions, to examine different pedalling actions from cyclists with different backgrounds. Special pedals were constructed to increase the degrees of freedom and allow the participants to self select their own preferred position without constraint. 3D video analysis was used at a fixed workload to determine kinematic variations and effects, and anthropometric characteristics were recorded for the purpose of analysing individual responses to the increased degrees of freedom.

This chapter has been submitted to the European Journal of Sports Sciences and is currently under review.

3.1 Introduction

Correct fit upon a bicycle is essential for improved performance, comfort and injury prevention (Silberman, Webner, Collina, Shiple, 2005). Previous research has focused around the optimisation of body orientation whilst cycling, both in terms of power production and aerodynamic benefit (Chapman et al., 2008a; Dorel, Couturier & Hug, 2009; Heil, Derrick & Whittlesey, 1997; de Vey Mestdagh, 1998; Savelberg, Van de Port & Willems, 2003), and the use of adjustable characteristics of the bicycle, such as seat tube angle (Price & Donne, 1997; Ricard, Hills-Meyer, Miller & Michael, 2006; Umberger, Scheuchenzuber & Manos, 1998) and saddle height (Bini, Hume & Croft, 2011; Peveler, Pounders & Bishop, 2007; Peveler, 2008; Sanderson & Amoroso, 2009), to achieve changes in relative placement of the rider in respect to the crankarms. The joint loads at the knee are also an important factor during cycling, not only for maximising effective power production to the pedal, but also associated with the risk of injury (Ericson & Nisell, 1987; Gregersen & Hull, 2003; Ruby, Hull, Kirby & Jenkins, 1992).

When analysing positioning on a bicycle, there are three points of contact to consider: the handlebars, saddle and pedals. Commercial bicycles allow for a large range of adjustment in terms of handlebar and saddle placement through the use of different sized frame sets and the attachment components (seatpost and stem). Conversely, however, there is a limited range of adjustment at the pedal, where only crankarm length (within a typical range of 165-180 mm) and a small amount of cleat adjustment can be made in order to position the foot. Cleats can be positioned to move the foot along the axle of the pedal towards and away from the crank (approximately 5 mm laterally per cleat), fore-aft on the pedal (5-7 mm range), to allow rotational freedom (release angle) and set the base angle of foot on the pedal. Orthotic inserts can also be used to alter the inversion/eversion of the foot.

Crank arm length within realistic ranges (145-170mm) (Martin & Spirdoso, 2001) and cleat/foot fore-aft positioning (Sickle & Hull, 1997; Vroemen, 2011) have been explored in the literature with equivocal effects, with no increase in maximal power output or improvement in economy. Inversion and eversion of the foot has also been explored before in combination with rotation of the foot (Wootten & Hull, 1992; Boyd, Neptune & Hull, 1997), but again with inconclusive results or in the form of case studies, limiting the conclusions that can be drawn. The construction of special pedals is required to analyse such variables. However instrumented pedals often increase stack height (Wootten & Hull, 1992; Boyd et al., 1997), which causes the circular motion of the pedalling stroke to be shifted upwards, changing the pedalling action from the norm.

It is known that lower Q Factors are more mechanically efficient (Disley & Li, 2011), and there is no biomechanical basis for 150 mm Q Factor to be optimal in terms of comfort or power production. In the field of motor control research, it is known that individuals are able to perceive affordances, in particular their optimal course of action during a task (e.g. Warren, 1984). What is unclear is whether cyclists, given free range of motion, will self select a Q Factor that is different from 150 mm.

Commercial road pedals utilise a cleat system whereby a composite or metal cleat is attached to the shoe and is able to be locked into and released from the pedal. Early pedal systems allowed no transverse rotation at the foot, which was associated with increased risk of knee injury (Holmes, Pruitt & Whalen, 1994). Today, popular pedal and cleat systems allow a maximum of 5-10 degrees of rotation at the pedal body before release (Look Cycle International, France; Shimano Inc., Japan), with some systems allowing non-centering ranges that are higher than this (up to 20 degrees, Speedplay Inc., USA). However, to the authors knowledge, there is no published scientific data to show that these ranges are optimal, and previous research has utilised only commercial pedals with limited release angles (Boyd et al., 1997). Similarly to self selection of Q Factor, it is currently unknown what maximum release angle, and base orientation of the cleat and foot to the pedal cyclists would choose given pedals that allow free range of motion. Joint loading and kinematic patterns have been explored whilst cycling, showing individual effects during the pedalling action (Gregersen & Hull, 2003;Chapman, Vicenzino, Blanch & Hodges, 2009). It is likely therefore that conventional cleat and pedal systems could present limitations to some cyclists due to individual variability during the pedalling stroke.

More experienced cyclists maintain better coordination (i.e. less overall variability) than novice cyclists (Chapman, Vicenzino, Blanch & Hodges, 2008b), and variability during repeated action in sport is an indicator of motor control and coordination (Bartlett, Wheat & Robins, 2007). The knee is the most unconstrained joint that performs action during the seated pedal stroke – motion at the hip is limited within a relatively small area as the cyclist sits upon the saddle, and the ankle joint is similarly laterally constrained by the foot's attachment to the pedal and the float available in the cleat. Therefore there is more freedom to move at the knee during the pedalling stroke, which results in knee variability being a good indicator of motor control and coordination during cycling. More experienced cyclists should have less variability than novice cyclists when extra degrees of freedom are involved, which could exacerbate any change in level of constraints (e.g. Q Factor and pedal angle).

Based upon these previous data on kinematic variability, the aims of this study are to examine whether a) commercial cleat and pedal systems provide cyclists with sufficient range of motion during the pedal stroke, by using pedals that are freely able to move, and b) whether the self selected pedalling action is different for stable and unstable cyclists.

It was hypothesised that: 1. The range of motion provided by commercial cleat systems (float) is smaller than what is exhibited by cyclists, due to individual variability in pedalling kinematics. 2. Knee variability is likely to increase when given complete free range of motion at the pedal, due to the extra degrees of freedom causing increased instability during the pedal stroke, and this increase will be less in more experienced cyclists. 3. Given free range of motion, cyclists are likely to adopt a different Q Factor than the fixed standard of 150 mm, due to intra- individual differences in pedalling mechanics.

3.2 Methods

3.2.1 Participants

Twenty-nine cyclists (15 male, 14 female, mass 70.4 ± 10.6 kg, height 176.2 ± 9.8 cm, age 23.3 ± 7.0 yrs) volunteered for the study and gave informed consent. All participants were accustomed to cycling exercise (>1 hr per week) and ranged from cycle commuters to triathlon and road cycling competitors . For the purpose of analysis, two groups of 12 participants were selected based upon knee variability as explained below. The study was approved by the local ethics committee.

3.2.2 Ergometer setup

Testing was performed upon a custom made narrow adjustable bicycle, permitting the use of narrower Q Factors (eg. 90mm), equipped with a torque sensor in the rear hub to measure power output (Powertap, Saris, USA), and mounted upon an electromagnetically braked turbo trainer to provide resistance (Tacx i-Magic, Tacx, The Netherlands). Custom ‘floating pedals’ were mounted upon the bicycle, which consisted of a 12 x 30 cm footplate equipped with retaining straps. A bushing was attached underneath the footplate and mounted upon an axle that projected from the crank, along with plastic sleeves either side of the pedal in order to either restrict or allow lateral movement of the pedal along the axle. During periods where the pedal was allowed to move laterally, the plastic sleeves were removed, permitting a range of effective Q Factor (ie. pedal location relative to a virtual crank, as the crank itself was fixed) from 90 mm to 370 mm. The 360º rotation of the pedal in respect to the horizontal axle was permitted by the addition or removal of retaining screws attached to a plate of needle bearings underneath the footplate.

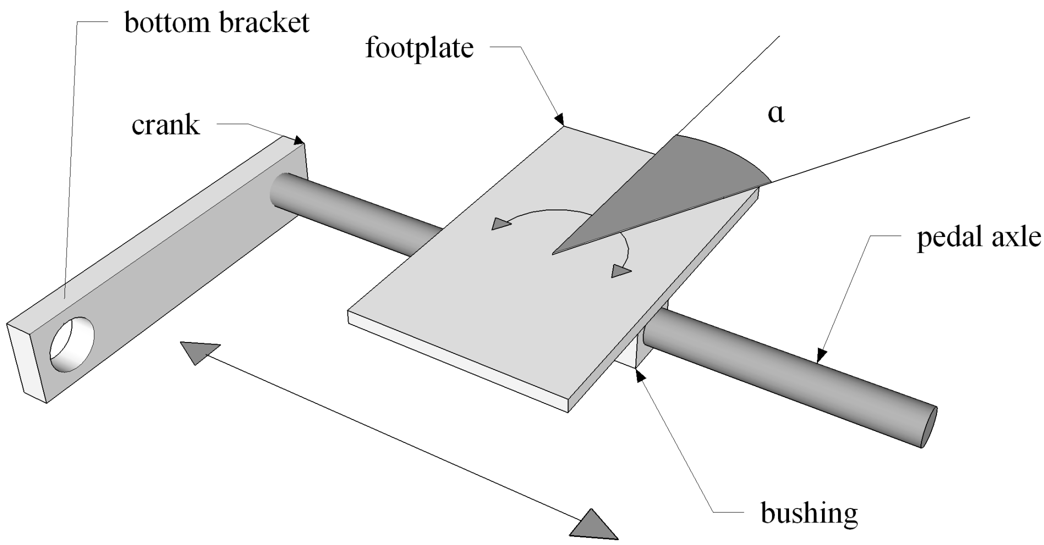

Figure 17. Floating pedal setup. Lateral freedom along the pedal axle was permitted during the lateral and free conditions, and rotational freedom permitted during the rotation and free conditions. Foot angle is represented by angle α

Saddle height was measured from the foot plate bed with the crank at the bottom of the pedal stroke (6 o'clock position) to top centre of the saddle. Due to the offset vertical seat tube, an inline measurement of the seat tube was not possible. Saddle height was set at 90% of greater trochanter height for all participants, representing typical recommendations (Ferrer-Roca et al., 2012) and handlebar location was self selected. Participants were required to complete the testing protocol in bare feet with no shoes, secured on the footplate with retaining straps. No shoes were used in order to minimize stack height. Key locations on the foot were marked using a washable pen in order to ensure that location on the pedal was kept constant between conditions.

3.2.3 Infrared kinematic recording

Seven reflective markers were placed on bony landmarks of the lower body: the superior anterior iliac crest, lateral femoral condyle, trochanteric fossa and lateral malleolus of each leg, and on the sacrum. In addition, markers were placed along the centerline of each pedal at the front (in front of the toe), rear (behind the heel) and also on the outside edge of the pedal, in line with the axle. Thirteen infrared cameras were used for the purpose of determining marker location, and data were collected at 100 Hz using Nexus software (Oxford Metrics Group, UK). A separate calibration was performed before each session, with an error limit of 0.3mm (mean residual) according to manufacturer recommendations . If error was above this value then calibration was repeated.

3.2.4 Experimental protocol

Participants were required to visit the laboratory on one occasion. After arriving at the laboratory handlebar and saddle height were set according to the details above. There was an initial warm up period of 5 min at a self selected intensity of <150 W, where the participants were mounted upon the adjustable bicycle with the pedals in a fixed condition, allowing no rotational or lateral movement. During data collection, participants were required to pedal at 90 rpm and 150 W for periods of 3 min, separated by 3 min of rest in order to minimize the effects of fatigue. 150 W was a comfortable and easily achievable power output for all of the participants analysed. Data were collected over a 30 sec period during the second minute of each 3 min trial. The participants were not informed of the period of data collection.

During exercise body position was standardised with the hands placed on top of the handlebars ("on the tops"), participants were instructed to look at a computer display showing cadence, mounted approximately 25 cm in front of the handlebars, and instructed not to look downwards at their feet.

Four conditions were used twice each, in the following order to progressively introduce extra degrees of freedom whilst pedaling, allowing the acute effect of introducing instability into the pedal stroke to be examined: fixed (no rotation and no lateral movement), lateral (lateral movement permitted but no rotational movement), rotation (rotational movement permitted but no lateral movement) and free (both rotational and lateral movement permitted). In between the lateral and rotation trials the feet were taken off the pedals in order to remove the rotational retaining screws, and replaced according to the landmarks marked on the feet.

The Q Factor in the fixed condition was set at 150 mm. Due to construction of the bearing and bushing system there was a small amount of lateral play in the fixed condition of ~1 mm either side of the pedal.

3.2.5 Analysis

Data were collected in 30 sec intervals representing 45 ± 1 pedal cycles. Raw data were exported and analysed at 100 Hz frequency. Q Factor was determined in mm by calculating the horizontal distance between the pedals using pedal markers, and averaged over the two trials for each condition.

Knee variability is represented by the standard deviation of movement of the lateral femoral epicondyle (averaged between left and right sides), along the frontal plane in mm.

Foot angle variability is represented by the standard deviation of the angle away from the sagittal plane at the foot (averaged over both feet), and mean foot angle is the average foot location during the data sampling period. A positive angle indicates that the foot is positioned "toe in" towards the bicycle, with a negative angle being "toe out".

Mean maximum foot angle is the greatest foot angle (averaged over both feet) away from the sagittal plane during the data sampling period.

3.2.6 Grouping

Participants (n=29) were ranked in order of knee variability during the FREE condition. The 12 subjects with lowest knee variability were grouped as stable (ST), and the 12 with highest knee variability were grouped as unstable (UST). The data for the remaining 5 participants was discarded.

3.2.7 Statistical Analysis

All data for the two groups were analysed using PASW Statistics version 17 (IBM, USA). Results are presented as Mean ± SD. Two way repeated measures analysis of variance (ANOVA) was conducted to determine main effects with Bonferroni correction. If the laws of sphericity were violated then the Greenhouse-Geisser correction was used. α was set at 0.05.

3.3 Results

Knee variability was lower in the ST group during the free condition compared with UST (ST = 12.8±1.7mm, UST = 23.9±4.7mm, $F(1,1)=60.076$, $p=.001$). There were 6 males and 6 females in each group. There was no difference in age between groups ($F(1,1)=1.614$, $p=.217$), nor was there a difference in height ($F(1,1)=0.001$, $p=.981$) or body mass

(F(1,1)=0.005, p=.946). Weekly training hours were higher in ST than in UST (ST = 8.8±4.0hrs, UST = 4.4±3.3hrs, F(1,1)=8.619, p=.008, η^2=0.281)

Group	Age (yrs)	Height (cm)	Mass (kg)	Training hours/week
ST (n=12)	25.1 ± 9.5	175.8 ± 8.5	71.4 ± 9.4	8.8 ± 4.0*
Male (6)	21.3 ± 2.1	181.5 ± 7.0	77.1 ± 9.5	7.8 ± 4.2
Female (6)	28.8 ± 12.7	170.2 ± 5.6	65.8 ± 5.2	9.8 ± 3.9
UST (n=12)	21.4 ± 9.5	175.8 ± 8.7	71.1 ± 11.6	4.4 ± 3.3*
Male (6)	22.8 ± 3.8	180.8 ± 7.5	75.3 ± 11.0	3.7 ± 3.5
Female (6)	20.0 ± 1.4	170.7 ± 6.9	66.9 ± 11.5	5.2 ± 3.2

Table 3. Participant characteristics and grouping. ST=Stable, UST=Unstable. * p<.01

There was no main effect of group on self selected Q Factor (SSQ) during the lateral condition between groups (F(1,1)=0.018, p=.894), however there was a small, but significant difference in SSQ during the free trial between groups (ST=137.3±16.8 mm, UST = 152.6±18.9 mm, F(1,1)=4.343, p=.049, η^2=0.165).

Knee variability increased by ~2.5 mm in the free condition compared with the fixed condition for UST (t=2.411,p=.035). ST remained the same (t=.648, p=.532).

Group	Knee variability		Self selected Q Factor	
	Fixed	Free	Lateral	Free
ST	12.6 ± 2.4	12.8 ± 1.7	144.9 ± 21.4	137.3 ± 16.8†
UST	21.4 ± 4.7*	23.9 ± 4.7*	146.0 ± 18.2	152.6 ± 18.9†

Table 4. Knee variability and self selected Q Factor. All values in mm. Knee variability increases in UST by ~2.5mm when moving from fixed to free conditions, whereas ST maintain knee stability as the extra degrees of freedom are introduced. * p=.035, † p=.049.

There was no difference in mean foot angle between groups in the rotation ($F(1,1)=0.307$, $p=.585$) or free conditions ($F(1,1)=0.731$, $p=.402$).

There was a significantly lower foot angle variability in ST compared with UST, in both the rotation ($F(1,1)=4.297$, $p=.050$, $\eta^2=0.163$) and free conditions (ST=2.0 deg, UST=2.6 deg, $F(1,1)=5.390$, $p=.030$, $\eta^2=0.197$).

There was a lower maximum foot angle in ST during the rotation (ST=15.9 deg, UST=19.3 deg, $F(1,1)=5.175$, $p=.033$, $\eta^2=0.190$) and free conditions (ST=15.5 deg, UST=19.6 deg, $F(1,1)=7.162$, $p=.014$, $\eta^2=0.246$) than UST.

Group	Foot angle variability (rotation)	Foot angle variability (free)	Maximum foot angle (rotation)	Maximum foot angle (free)
ST	2.0 ± 0.6	2.0 ± 0.4	15.9 ± 3.5	15.5 ± 2.6
UST	2.6 ± 0.7*	2.6 ± 0.7*	19.3 ± 3.9*	19.6 ± 4.6*

Table 5. Foot angle variability and maximum foot angle between groups in the rotation and free conditions. All values in degrees. * significant difference between groups, p<.05.

3.4 Discussion

The aims of the study were to compare the range of motion permitted by standard clipless cycling pedals with that of an unconstrained pedal, and whether this differed between stable and unstable cyclists. The Q Factor and the angle of rotation of the foot along the vertical axis, which have little to no exploration in previous study, were found to be different between stable and unstable cyclists.

In this study stable cyclists were found to exhibit less variability at both the knee and the foot compared with unstable cyclists. The manipulation of degrees of freedom caused no change in the coordination of already stable cyclists, but resulted in changes of the movement pattern of unstable cyclists.

The results partly support the hypothesis by showing that stable cyclists' SSQ of ~137 mm in the free condition is lower than unstable cyclists (~153 mm, remarkably close to the standard 150 mm found on a typical road bicycle), however this difference is only apparent when given complete free range of motion (both rotational and lateral freedom), rather than just lateral freedom. Therefore as more degrees of freedom are introduced into the pedalling action, more coordinated cyclists choose a lower Q Factor that tends towards the more mechanically efficient Q Factors of < 150 mm (Disley & Li, 2011). In the present study, degrees of freedom were introduced progressively during the pedalling task, however future work could be conducted with randomized level of freedom and the effect upon pedalling kinematics.

What is unclear from the data available is whether the unstable cyclists, who train for less hours, are more mechanically efficient at Q Factors closer to 150 mm, given their SSQ of 153 mm. The choice of a ~16mm wider Q Factor for the unstable cyclists could be due to an inability to fully explore the degrees of freedom presented during the experiment, therefore only choosing a Q Factor which is similar to standard. Further study is required in order to determine whether mechanical efficiency is increased at SSQ, and this difference implies that coordination during cycling (in terms of knee and foot variability) may play a role in the determination of the optimal positioning for the individual cyclist.

The maximum foot angle at the pedal is here shown to be greater than popular commercially available cleat systems in both groups. This angle is less (~16 deg) in stable cyclists compared with unstable (~19.5 deg), and is the same regardless of whether lateral freedom is present. This supports our second hypothesis that many commercial cleat systems provide a limitation for the cyclist by not allowing the foot to move freely during the pedal stroke. This could result in forces being transferred up through the knee as the foot is constrained at points of maximum rotation, higher than the release angle of the cleat, which could lead to patellofemoral injury if sufficient loads are present across the frontal plane (Schulthies, Francis, Fisher & Van De Graaff, 1995). Conversely, it could be argued that providing a limit of maximum rotation is advantageous for power production, as the direction of force application can be maintained within a stricter band, and the risk of injury is outweighed by the power production benefit. In this study 3-axis forces were not measured at the pedal, as the bushing and needle bearing system that provided the range of adjustment required would make measuring force difficult. Having determined that the characteristics of the pedalling action are different from commercial systems, further study is required in order to explore the applied force and joint loading when rotational freedom is manipulated. The work of Boyd et al. (1997) explored rotational freedom and moments at the knee, however using a pedal system that provided limitations previously described.

Coordination in cycling should be focused around the knee as the active joint with the greatest freedom to move during the pedal stroke, and is also the area greatest at risk of injury (Ericson & Nisell, 1987; Ruby et al., 1992; Elmer et al., 2011). The results supported the third hypothesis, that knee variability would increase with the introduction of extra degrees of freedom, with stable cyclists being able to manage this increase in freedom, and thus maintaining their coordination (Bernstein, 1967). Unstable cyclists exhibit a ~2.4 mm increase in knee variability when extra degrees of freedom are introduced. It is possible that unstable cyclists require more time to explore and subsequently exploit the additional degrees of freedom, whereas stable cyclists are able to manage the acute effect of allowing a change in range of motion.

The difference in variability is mirrored in previous research examining variance in muscular recruitment patterns between novice and highly trained cyclists, which found that the more experienced cyclists exhibit less variability than novice (Chapman et al, 2008b). There is very little data on the differences in kinematics between trained and untrained cyclists (Bini & Diefenthaeler, 2009; Carpes et al. 2011), and although this study did not include a large population of elite cyclists, the finding that cyclists who are more stable train for more hours than unstable could indicate that training hours have an effect upon coordination. This influence upon coordination whilst cycling could be further explored in future study by using groups matched for training hours to examine how coordination may be affected, as well the use of a relative workload intensity (eg. 60% of peak power output) rather than the fixed 150 W used in the current experiment.

A limitation of 3D digital stereophotogrammetry using human participants in dynamic movement is the influence of soft tissues (STA) upon data analysis. Inter-subject variability can result in errors as markers placed upon the skin can move relative to the desired joint or bone location, as well as elastic components of the soft tissue varying during action and between subjects (Leardini, Chiari, Della Croce & Cappozzo, 2005). In order to avoid invasive percunateous techniques that could affect the pedalling action, quantification of individual STA would provide a more detailed an accurate representation of personal and group characteristics.

In conclusion, the data in this study show that kinematic differences exist between stable and unstable cyclists when pedalling upon a novel pedal platform that is free to move during the pedal stroke, and that the level of motor control creates different needs for the individual cyclist. Consequently, commercial cleat systems and the Q Factors provided by cranks may possess insufficient ranges of adjustment, and further investigation is required to determine in what way this could be a limiting factor for power production and injury prevention during cycling. Future work should compare SSQ and standard Q Factors, and how gross mechanical efficiency and oxygen uptake are affected whilst cycling.

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4 OPTIMUM Q FACTOR AND LABORATORY TIME TRIAL PERFORMANCE

The previous study found that more stable cyclists tended to train for more hours and choose a Q Factor that was below standard (<150mm) which in the first study provided a performance benefit at submaximal intensities. This study looked to use trained cyclists working at a high level of aerobic capacity in the form of a time trial, using different Q Factors from 90-180mm to see whether the improvement in gross mechanical efficiency at <150mm was mirrored. Trained male cyclists used to time trial competition (including two national record holders) performed four time trials with no prior knowledge of Q Factor and its effects for the purpose of evaluating performance at maximal capacity.

This chapter has been submitted to the Journal of Science and Medicine in Sports and is currently under review.

4.1 Introduction

No data have been published on what Q Factor will be optimal for the individual cyclist. Previous research has investigated step width whilst walking (Donelan et al., 2001;Arellano & Kram, 2011) where preferred step width results in a lower metabolic cost compared with wider or narrower than preferred. During cycling, crank arms (and therefore Q Factor) are fixed whilst riding, unlike the freedom of movement permitted during unrestricted walking. By manipulating Q Factor in order to present the cyclist with a range of movement patterns, it has been found that lower Q Factors (<150mm) are 1.5-2% more mechanically efficient at submaximal intensities (Disley & Li, 2012). However, it is unclear whether this improvement is mirrored when working at a high level of aerobic capacity, such as a time trial (TT).

The aims of this study are to examine whether Q Factors <150 mm provide improvements in power output at maximal aerobic capacity, and the effect of different Q Factors from optimal on TT performance.

It is hypothesized that:

1. Mean power output during a 24 min TT will be greater at Q Factors <150mm.
2. Deviation away from the Q Factor that results in optimal performance (OQ) will cause a further decrease in power output.

4.2 Methods

4.2.1 Participants

Ten trained male cyclists (VO_{2max} 60.7 ± 6.8ml.kg.min^{-1}, peak power output (PPO) 361.4 ± 23.0w, mass 77.3 ± 6.1kg, height 182.7 ± 5.5cm, age 23.7 ± 6.0 yrs) volunteered for the study and gave informed consent. All participants had a >2yr history of competition in TTs and cycle racing. The study was approved by the local ethics committee.

4.2.2 Setup

Testing was performed upon a custom cycle ergometer, adjustable in terms of handlebar position, saddle height, seat tube angle and Q Factor. A proprietary crank system with removable bottom bracket axles provided Q Factor adjustment. Crank length was set at 170 mm and participants' own pedals and shoes were used throughout. A Powertap (Saris, USA) mounted upon a resistance unit (Tacx i-Magic, Tacx, The Netherlands) was used in order to measure power output and cadence. The Powertap has been shown in previous research to be a reliable and repeatable device (Bertucci et al., 2005; Peiffer & Losco, 2011).

4.2.3 Protocol

Participants were required to visit the laboratory on five occasions. The first visit consisted of an incremental exercise test in order to determine VO_{2max} and peak power output (PPO). Participants arrived at the laboratory and were permitted to adjust the ergometer to their preferred riding position. This was recorded and then replicated for all subsequent trials. The test consisted of 3 min stages at self selected cadence and 150 mm Q Factor, starting at 200 w and increasing by 30 w every 3 min until volitional exhaustion. During the final ~60sec of each stage, expired gas was collected using Douglas bags in order to determine VO_{2max}. PPO represents the highest mean 60sec power output during the trial, and VO_{2max} represents the final ~60sec bag collected during the trial at an RER >1.15.

Before arriving at the laboratory for visits 2-5, participants were required to complete a 12 hr food diary and replicate it before each trial. Visits 2-5 were conducted using four different Q Factors (90, 120, 150 and 180 mm) which were randomly assigned for each visit. Participants warmed up for 15min (two 5 min efforts at 60% PPO and active recovery of 3min at <100 w). This was followed by the 24 min TT at maximal intensity. Participants were provided only with a display showing time and were requested to complete the TT at as high an intensity as possible. Resistance of the electromagnetically braked unit was self selected during the trial. Position was standardized with hands on the tops of the handlebars and water provided ad libitum. Participants were all trained cyclists accustomed to TT efforts on an indoor trainer, and therefore no familiarization trial was required (Sporer & McKenzie, 2007;Thomas et al., 2011).

4.2.4 Analysis

Repeated measures ANOVA was used in order to determine main effects of Q Factor on power output, cadence and pacing, and post hoc analysis was performed using Fisher's t tests where necessary. If the laws of sphericity were violated, Greenhouse-Geisser correction was used. Pacing during the TTs was examined by splitting the mean power for each Q Factor into four 6 min "bins". Correlations represent Pearson correlation coefficients. α was set at 0.05.

4.3 Results

	Q Factor (mm)			
	90	**120**	**150**	**180**
Power output (w)	287.7 ± 28.7	292.8 ± 29.8	290.1 ± 26.4	288.0 ± 30.4
Cadence (rpm)	98.5 ± 8.6	97.7 ± 5.5	99.7 ± 7.0	98.8 ± 7.0

Table 6. Power output and cadence during the four TTs. All values Mean ± SD.

No overall significant differences in PO were found between TTs at the four different Q Factors ($F(1,1.652)=0.738$, $p=.470$). No difference was seen in freely chosen cadence during the TTs ($F(1,2.380)=1.412$, $p=.267$).

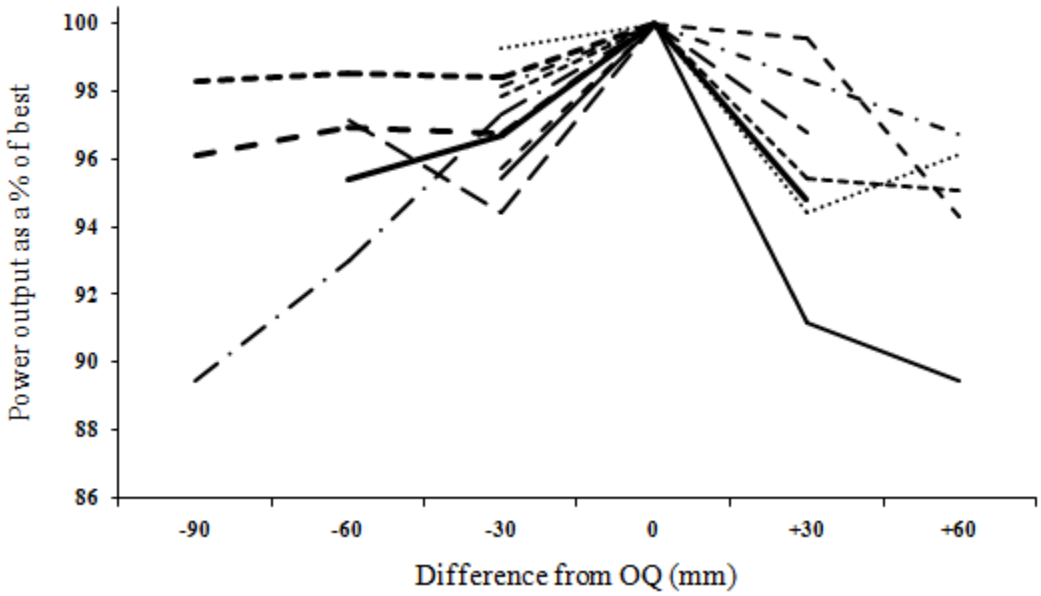

Figure 18. Decrease in power output as Q Factor deviates from OQ. Each line represents one participant. Mean OQ was 144mm.

Mean Q Factor at the highest power output was 144.0±8.7mm. As Q Factor was increased or decreased from OQ power output reduced by ~3.6%.

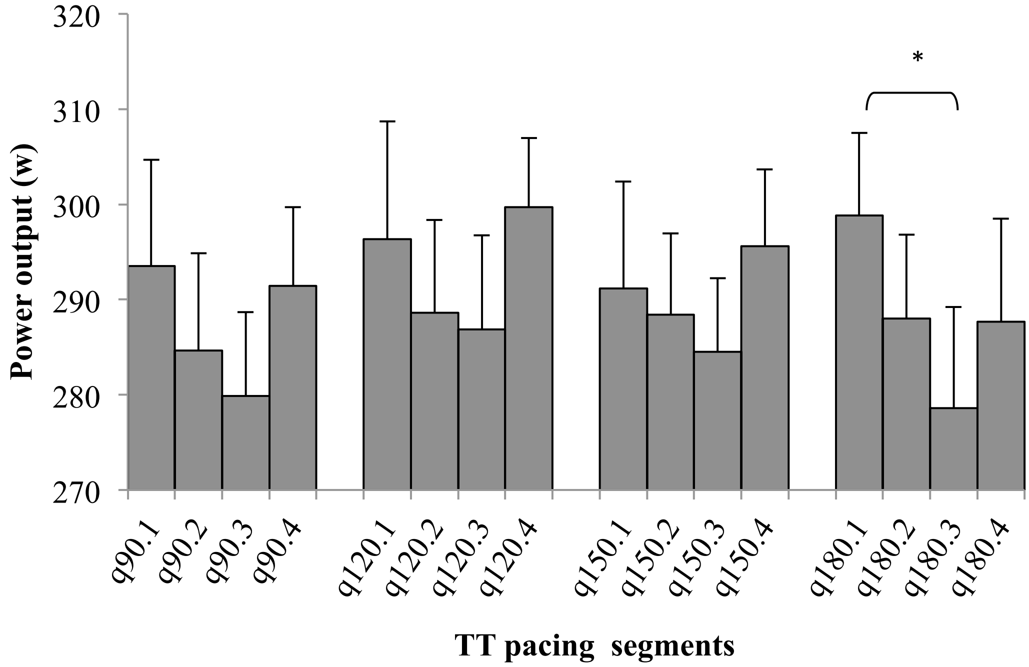

Figure 19. Pacing strategy during the TTs.

Pacing strategy was significantly different from even in the Q180 TT (F(1,1.887)=6.442, p=.009), and characterized by a slower third quarter (p<.016).

4.4 Discussion

When normalized to best performance, a continual decline in power output was seen as Q Factor deviated from optimal (144 mm).

A deviation of 22.3mm saw a drop in power output during the TT of 3.6%, or 13.1 w, up to a maximum of 5.5% or 16.4 w at Q Factors 45 mm away from OQ. During a 16km outdoor TT lasting ~24min in duration, this would result in a ~26-36sec increase in finishing time.

In the present study a remarkable increase in power output is seen at OQ compared with the other trials, ~2% higher than model predicted best power. This finding agrees with the work of Donelan et al, (2001) in step width during human walking: optimal step width resulted in a large decrease in oxygen cost compared with widths that were wider or narrower.

Previous data exploring OQ at submaximal power outputs found an increase in gross mechanical efficiency at <150mm (90 and 120mm (Disley & Li, 2012). In the present study no participant recorded their best performance at 90mm, which suggests that the benefit of such a low Q Factor is reduced as intensity increases. This may be due to differences in muscular recruitment that are only seen at higher power outputs, however the level of activation of major cycling muscles was not measured here and should be the subject of future research. Nevertheless, mean OQ in the TTs was <150mm, which suggests that 150-155mm (typical Q Factors for road and TT racing bicycles) may not, on average, result in the best performance during a TT. It should be noted that self selected cadence was not found to be different between the TTs: large scale changes in muscular activation have been shown to be related to cadence (Sanderson et al., 2006; Bieuzen et al., 2007; Dantas et al., 2009) and so we might expect that substantial muscular recruitment changes would be reflected in a difference in cadence.

The results of the pacing analysis showed that Q180 resulted in a non-even pacing strategy, characterized by a hard start (mean power for first quarter = 298.9 w) and easier third quarter (278.6 w) compared with mean power (288.0 w). There was no significant difference between pacing bins for the other Q Factors. Non even pacing strategies in TTs >5 min in duration have been shown to result in detrimental performance (Ham & Knez, 2009;Peveler & Green, 2010; Thomas et al., 2011a;Thomas et al., 2011b), although here there was no significant difference in overall mean power between the TTs. It is unclear why the Q180 trial should result in such a variable pacing strategy compared with the other trials, as although 180 mm is a non standard Q Factor for a cyclist accustomed to road TTs, 90 and 120 mm also represent non standard Q Factors. It is possible that perception of effort is altered at different Q Factors, and at the widest Q Factor this altered perception results in a non-optimal pacing strategy. If perception of effort is decreased at OQ, this will result in a higher mean power output.

4.5 Conclusions

Mean OQ was found to be 144 mm in the present study. OQ differed between participants, however it is important to ensure that the cyclist is riding at the correct Q Factor, as deviation away from OQ can cause a performance decrease of >5%. Further study is required in order to establish a method for predicting OQ.

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5 METABOLIC AND KINEMATIC EFFECTS OF SELF SELECTED Q FACTOR DURING BIKE FIT

This final study was designed to explore how an individual's own self selected Q Factor affected gross mechanical efficiency and kinematics compared with the standard Q Factor of 150mm and wider/narrower Q Factors**.** In addition, static and dynamic testing was performed in order to find a technique that could predict a cyclist's self selected Q Factor. Trained cyclists were recruited and performed submaximal pedalling using the custom floating pedals to determine self selected Q Factor, followed by using their own shoes and pedals at a range of Q Factors whilst concurrently measuring gross mechanical efficiency and kinematics of the lower limbs.

This chapter has been accepted by Research in Sports Medicine and is due for publication in 2014.

5.1 Introduction

The bicycle has undergone many evolutions over its ~150yr history. The original velocipede required the pilot to run or walk, partially suspended and supported by a frame and saddle equipped with two wheels front and rear. The major difference between later bicycles and the velocipede is the chainwheel drive system, which requires the pilot to be suspended off the ground. The introduction of the chainwheel and crank arms creates a further fixed point of contact for the rider (as well as the handlebars and saddle), reducing the kinematic freedom of the lower limbs away from the locomotive action that propelled the velocipede.

In scientific research, due to the popularity of the bicycle as a form of exercise and transport, the optimisation and self selection of position upon the bicycle has been explored, mainly through the location of the handlebars and saddle (e.g. de Vey Mestdagh 1998; Silberman et al. 2005; Ferrer-Roca 2012). Nearly all research has focused upon adjustments along the sagittal plane, such as fore-aft and vertical location of the saddle, and saddle angle (Heil, Wilcox & Quinn 1995; Price & Donne 1997; Umberger, Scheuchenzuber & Manos 1998; Peveler 2008; Fonda et al., 2011; Bisi et al. 2012), location of the handlebars and hand position (Usabiaga et al. 1997; Duc et al. 2008) and length of the crank arms (Martin & Spirduso 2001; Barratt et al. 2011). Yet the human body moves in 3D space: recent research has examined how changes in positioning of the feet on the pedals along the frontal plane (known as Q Factor) can affect physiological parameters such as gross mechanical efficiency (Disley & Li, 2012a).Therefore, in order to optimise human interaction with the bicycle, location and movement in 3D space should be taken into account .

Individual morphology of cyclists is rightly used to explain differences in the optimal setup of cycling equipment both in the laboratory and outdoors (de Vey Mestdagh 1998; Silberman et al. 2005; Laios & Giannatsis 2010). Work examining self selection of this position has shown that cyclists are able to optimise their setup based upon their individual morphology and anthropometric characteristics. Research has been performed on saddle height which reflects this (Peveler 2008; Sanderson & Amoroso 2009; Ferrer-Roca et al. 2012), and provided calculated ranges within which the cyclist should choose their own optimal saddle height, for example 108.6-110.4% of inseam length (Ferrer-Roca et al. 2012). Ultimately, the optimal position is decided by the cyclist.

In order to determine the effect of changing position, performance based tests (Gnehm et al., 1997; Ashe et al. 2003; Jobson et al. 2008) and physiological markers such as oxygen consumption and efficiency (Grappe et al. 1998; Leirdal & Ettema 2011; Bisi et al. 2012) have been used in order to detect improvements.

In addition, the reasoning behind a self selection of position can be associated with injury and comfort. The knee is the most unconstrained joint during the pedal stroke, compared with the hip (supported by the saddle) and ankle (whose range of motion is constrained by the pedal circle). Although the knee must move within an arc in all three axes, the possibility for deleterious movement leads to knee pain being a critical factor in cycling injury (Silberman et al. 2005; Bini, Hume & Croft 2011). Knee pain can affect all cyclists from amateurs to professionals (Wanich et al. 2007; Clarsen, Krosshaug & Bahr 2010), and low knee movement along the frontal plane has been suggested as a factor that can reduce pain and increase comfort (Silberman et al. 2005; Abt et al. 2007). Previous research has shown that more stable cyclists in knee movement along the frontal plane tend to be more experienced (Disley & Li, 2012), indicating that knee movement in the frontal plane could be affected by training.

The bicycle was designed to use the locomotive ability of the human body for assisted forward motion. Any self selection of the suspended position on the bicycle for comfort or injury purposes should therefore be based upon the action of bipedal walking. At submaximal levels when movement patterns begin to diverge from the simple seated cyclical motion there is an increase in oxygen cost (Ryschon & Stray-Gundersen 1991; Tanaka et al. 1996) and/or breathing frequency (Millet et al. 2002; Harnish, King & Swensen 2007).

The combination of knee movement and efficiency has not been explored previously. We propose that they are linked –excessive movement in the frontal plane during the pedalling stroke is likely to produce non effective tangential forces at the pedal (Bini et al., 2013; Blake et al., 2012), resulting in a lower applied power output to the bicycle, and therefore lower efficiency.

Self selected Q Factor (SSQ) on a bicycle is likely to be related to where the feet would naturally fall when allowed kinematic freedom, in the same way as varus/valgus motion for individuals (Hannaford et al., 1986; Sanderson et al., 1994) and also related to locomotive gait. Simple unrestricted tasks such as suspending the lower body freely, and examining foot placement during gait could predict SSQ. The aims of the study were to determine whether the use of SSQ would decrease knee variability and improve efficiency, and whether SSQ can be predicted off the bike.

The authors hypothesise that:

1. When given free range of motion, the use of SSQ will decrease variability at the knee compared with Q Factors wider or narrower than SSQ
2. SSQ will provide a higher gross mechanical efficiency than wider or narrower Q Factors
3. SSQ can be predicted using suspension and locomotion tasks.

5.2 Method

10 trained cyclists (7 male, 3 female, 27 ± 10 years old, 71.4 ± 8.1kg, 179.6 ± 5.0cm. Peak power output (PPO) reached during the incremental exercise test was 321 ± 32w and VO_2 max 56.0 ± 7.0 ml.kg.min^{-1}) volunteered to take part in the study and provided informed consent. The study was approved by the local ethics committee. Participants visited the laboratory on three occasions, all separated by >48hrs.

5.2.1 First visit

The first visit consisted of an incremental test to exhaustion to determine VO_{2max} and PPO. All testing was performed upon an adjustable cycle ergometer, equipped with a Powertap torque measuring device (Powertap Elite+, Saris, USA) to record power, and mounted upon a Computrainer Pro (Racermate, USA). Participants used their own shoes, and selected their own handlebar and saddle position which were recorded and replicated for subsequent trials. Crank length was set at 170 mm for all trials.

For the incremental test, after a warm up period of <8 min at <100 w, participants began pedalling against a fixed resistance of 100 w (female) or 200 w (male), increased by 30 w every 3 min until volitional exhaustion. Expired gas was collected in Douglas bags during the final ~1 min of each 3 min stage in order to determine respiratory variables. PPO represents the highest 1 min power reached at the end of the incremental test, and VO_{2max} the peak value from the final Douglas bag.

5.2.2 Second and third visit

In the second and third visit, participants were instrumented with reflective markers for the purpose of 3D kinematic analysis, in nine locations of the lower body: lateral malleolus, medial malleolus, lateral femoral epicondyle, superior anterior iliac crest on both sides, and upon the sacrum. In addition, for bare foot analysis markers were placed upon the intermedius phalanx of the digitus pedis secundus and distal edge of the calcaneus, or the corresponding surface locations along the centre line of the cycling shoe. Locations were marked with a washable pen, and photographs taken to ensure repeatable marker placement. Nexus software (Oxford Metrics Group, UK) was used to determine marker location using thirteen infrared cameras recording at 250Hz.

After instrumentation, participants completed two tasks. The first consisted of walking a distance of 6 m barefoot before stepping onto a box 15 cm high at normal walking speed. 8 trials were conducted, 4 trials stepping up with the right foot and 4 trials with the left foot, and 3D kinematic data recorded throughout each trial, and mean marker location taken for the static position on the box, as well as mean step width during the stepping period. For the second task participants were required to suspend themselves off the ground for a period of >5 sec in the gymnastic support position, by use of the arms placed on two parallel bars placed either side of the body above hip height. 6 trials were completed, and participants instructed to relax their lower body and look forward during suspension. 3D kinematic data were recorded during suspension for 5sec and the mean marker location taken.

Participants were then mounted upon the adjustable ergometer, equipped with custom "floating pedals" allowing free movement of the foot in the lateral plane whilst cycling (Disley & Li, 2012b). Workload was set at 60% of PPO and participants instructed to pedal at 90 revolutions per minute (rpm) for 5 min, during which kinematic data were recorded for 10 sec at the end of each minute in order to determine self selected Q Factor (SSQ). Participants were instructed to look at a computer screen mounted upon the handlebars to ensure a consistent cadence and not to move their hands from the handlebars whilst pedaling.

After a rest period of 4 min, 4 x 8 min bouts of pedaling were conducted at 60% PPO and 90rpm, separated by 4 min of rest. Participants own pedals and shoes were used with 4 different Q Factors: SSQ, SSQ – 30 mm (SSQ-30), SSQ + 30 mm (SSQ+30) and 150 mm (Q150). Q Factor was manipulated using axles of different lengths combined with spacers to move the cranks towards and away from the centerline of the bicycle in 1 mm increments. Minimum possible Q Factor was 92 mm. The order of Q Factors was randomized. During each bout of pedaling, expired gas was collected using two Douglas bags for periods of ~120 sec and ~90 sec for the purposes of determining gross mechanical efficiency (GME). 3D kinematic data were collected for 4 x 10 sec periods at 1, 2, 3 and 8 min.

5.2.3 Analysis

All data presented represents the average of visits two and three for each participant. Two visits were used for the purpose of evaluating whether a training effect was present. Raw 3D kinematic data were exported at 250Hz for analysis.

Step width measured via Vicon raw data represents the lateral distance in mm between the medial malleoli, once static upon the step box during the first dynamic task. Hanging ankle distance represents the mean lateral distance in mm between the medial malleoli during a 5 sec period of suspension.

SSQ represents the average SSQ during the 5 data collection periods.

Knee variability during the 8 min bouts of pedaling was calculated as the standard deviation of movement of the lateral femoral epicondyle marker along the frontal plane. Data were averaged between left and right legs over the 4 data collection periods. % best knee stability represents the knee variability for one Q Factor condition divided by the best (i.e. lowest) knee variability achieved for any Q Factor.

GME was calculated using the ratio of work accomplished in $kcal.min^{-1}$ to energy expended in $kcal.min^{-1}$ (Disley & Li, 2012a). The Douglas bags were evacuated of residual volume before use to minimize potential error. GME was only calculated if RER remained <1.00, and was averaged over the two bags for each Q Factor. The same dry gas meter (Harvard, UK) and gas analyser (Servomex, UK) were used during testing to ensure repeatable analysis of expired gas.

Data were analysed using PASW Statistics version 17 (IBM, USA). Results are presented as Mean ± SD. Two way repeated measures analyses of variance (ANOVA) were conducted to determine main effects using Bonferroni correction. The Greenhouse-Geisser correction was used if the laws of sphericity were violated. Correlations represent Pearson correlation coefficients – any data points more than 2SD away from the mean were removed. α was set at 0.05.

5.3 Results

Condition	Q Factor (mm)	GME (%)	Knee variability (mm)
SSQ-30	114 ± 10	18.42 ± 0.37	8.0 ± 1.6
SSQ	142 ± 12	18.65 ± 0.31	7.7 ± 1.6
SSQ+30	172 ± 12	18.37 ± 0.59	8.0 ± 1.8
Q150	150 ± 0	18.62 ± 0.44	7.9 ± 1.8

Table 7. Q Factor, GME and knee variability for the four conditions. No significant differences were found between GME or knee variability using the different Q Factors ($p>.05$).

No significant differences were found between GME ($F(1,3)=1.266$, $p=.306$) or knee variability ($F(1,2.284)=0.756$, $p=.498$) among the different Q Factors (Table 6). Mean SSQ across all participants was 142 ± 12 mm. Due to previously explained restrictions in minimum Q Factor, mean SSQ-30 was 114 mm rather than 112 mm as some participants adopted a low SSQ (<140mm).

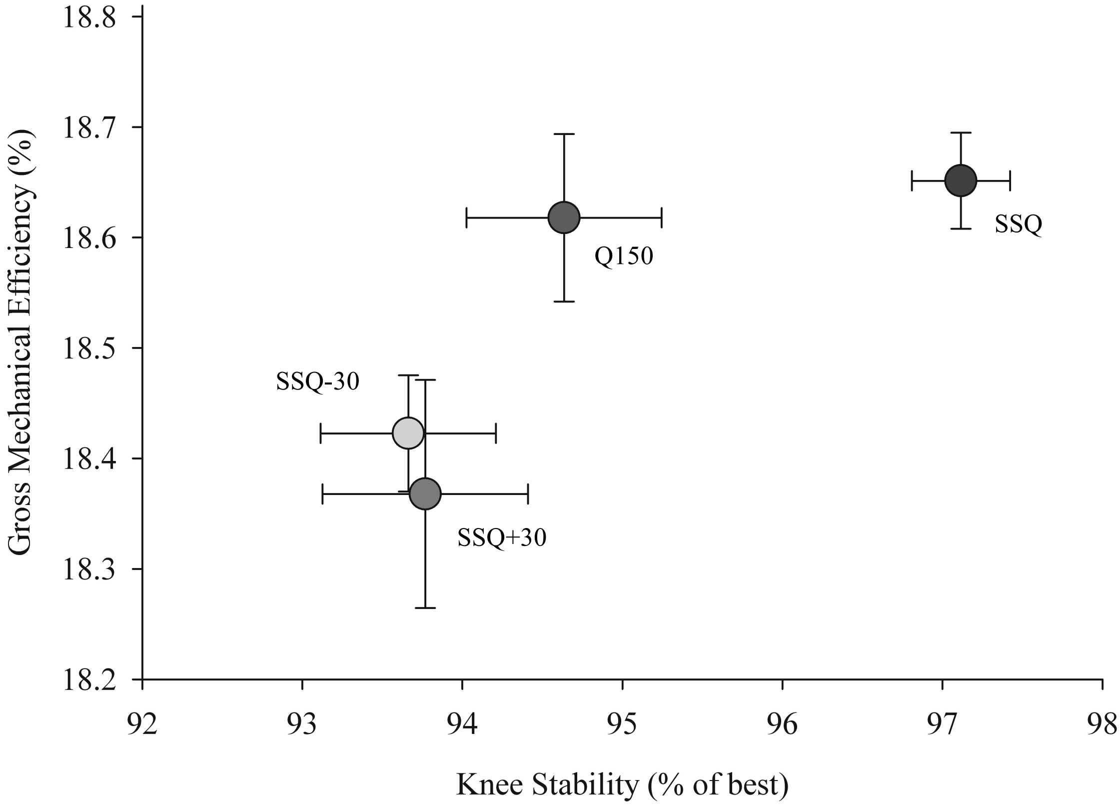

Figure 20. Gross mechanical efficiency and % best knee stability. Error bars represent the standard error across all participants for both GME and knee stability. Higher % best knee stability represents a more stable knee whilst pedalling. SSQ (142mm) provides the best combination of GME and knee stability, in contrast to SSQ+30 and SSQ-30 which have both lower GME and knee stability

When knee variability was normalized to best (i.e. lowest) performance, SSQ (142 mm) presented the best combination of GME and knee stability (Figure 1). At Q Factors 30 mm higher and lower than SSQ (SSQ+30 and SSQ-30), knee stability decreases with a concurrent decrease in GME.

A strong correlation was found between SSQ and hanging ankle distance during the hanging task (R^2=0.794, p<.002; Figure 2). The Y intercept of the equation for this relationship (y =

0.569x + 114.74) implies a minimum Q Factor of ~ 115 mm predicted from hanging ankle distance.

However the walking step task resulted in a step width that had poor correlation with SSQ (R^2=0.091). Step width ranged from 37 mm to 139 mm with a mean of 70 mm.

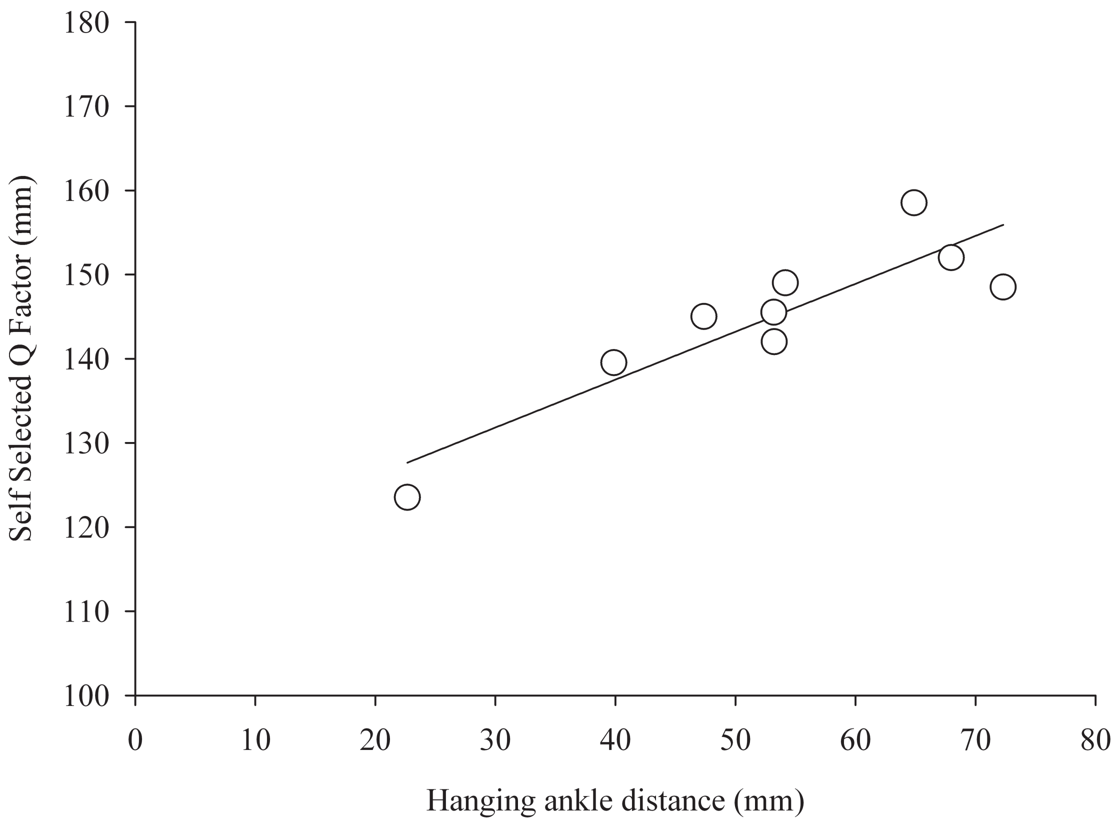

Figure 21. Relationship between Self Selected Q Factor and distance between the medial malleoli (both in mm) during the hanging task. One outlier removed. R2=0.794, p<.002.

No significant differences were found within participants for any of the dependent variables measured between visits two and three, with CV = 4.64%.

5.4 Discussion

Self selected Q Factor represents a part of the appropriate adjustments to be made to a bicycle to ensure an optimal fit. In the present experiment a range of Q Factors above and below SSQ were used to determine effects upon kinematic and metabolic variables. SSQ provided the best combination of knee stability and gross efficiency, compared with SSQ+30, SSQ-30 and Q150. SSQ can be predicted by use of a simple hanging task.

Previous work exploring GME and Q Factor has shown that lower Q Factors (<150 mm) provided higher GME than wider Q Factors (>150mm) (Disley & Li, 2012a). Here, SSQ was 142mm, comparable with previous data using a range of cyclists (145 mm; Disley & Li, 2012b), however there was no significant difference in GME alone between the different Q Factors. It is possible that the smaller range explored in this study (58mm) represents an upper detection limit in the determination of optimal Q Factor on the basis of GME alone, compared with previous data (range of 90 mm; Disley & Li 2012a). The same can be said for knee stability, but once normalised to personal best stability and compared alongside with GME, a trend occurs where the further the Q Factor deviates from SSQ, the more GME and knee stability decrease. Similar trends have been shown in time trial performance as it relates to an individual's optimal Q Factor (Disley & Li, 2012).

The combination of highest GME and best knee stability found at SSQ partially supports the first two hypotheses. When cyclists were permitted to ride at SSQ, this resulted in a positive kinematic and metabolic combined effect. The potential for both an improvement in GME and a reduction in knee variability allows the cyclist to cycle faster with potentially a lower risk of injury (Silberman et al. 2005; Abt et al. 2007). The focus on the knee joint is important due to the prevalence of knee injury during cycling and the range of motion permitted. Compared with the hip and ankle joints (and those of the upper torso), the knee joint is comparatively unconstrained and free to move during pedalling, allowing maladaptive technique to cause injury and clinical pain. Further study should examine the potential improvements in knee kinematics with changes to the bike setup, and perhaps how training can affect changes in abduction and adduction knee angle.

The hanging task provided a strong correlation between ankle distance and SSQ. This task allowed the participants to adopt an unconstrained position of the lower limbs. Upon the bicycle the cyclist is suspended from the saddle, the hands steering and supporting the forward leaning torso, and feet rest upon the pedals. The custom floating pedals allow the cyclist complete freedom of motion during the pedal stroke, which here is similar with the freedom of motion allowed by the unconstrained hanging lower limbs. The intercept of the y axis in Figure 2 should therefore provide a theoretical minimum Q Factor of 115mm, which compares favourably with the results of previous experiments where the minimum Q Factor exhibited by trained cyclists was >110mm (Disley & Li, 2012b).

No relationship was found between the walking step task and SSQ, and this could be related to balance issues: as the participants stepped up onto the box, the resulting stance width was a result of both the anthropometric characteristics of the individual and the need to remain balanced. This could have limited the minimum stance width. As walking step width has an effect on economy of walking (Donelan et al., 2001), it was hypothesised that the lower limbs may choose an SSQ closest to walking step width, but this was not found here.

There is need for further analysis of cyclists with a much larger range of ability than the trained cyclists in the present study. The use of a hanging task to predict SSQ could perhaps allow the untrained or inexperienced cyclist to reduce any knee variability to a greater extent than that displayed here. The simplicity of the task would allow it to be conducted without the need for complex equipment, which in turn would permit the analysis of cyclists outside of the laboratory. Indeed, recommendations on Q Factor could be provided to the cyclist at point of purchase in order to reduce risk of injury and improve efficiency, in a similar manner to saddle height (de Vey Mestdagh 1998; Ferrer-Roca et al. 2012). Future study of bicycle fit should examine whether other variables, such as handlebar width and saddle width have an effect on physiological and biomechanical factors.

The exploration of difference planes of motion during the process of bicycle fit is therefore essential for an holistic optimisation. SSQ can be predicted using a simple hanging task and provides the best combination of GME and knee stability, allowing for increased comfort, speed, and a lowered risk of injury.

The present study provides new data about optimising the position on a bicycle and how a simple test off the bicycle can inform bicycle fitting and potential for injury prevention. The data is limited to trained participants and without including other alterations in bicycle geometry. Further study might explore the effect of changing Q Factor on long term cycling kinematics, in conjunction with alterations in saddle height and handlebar location.

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6 DISCUSSION

6.1 Aim

The aim of this thesis was to explore the effect of manipulating Q Factor on cyclists' physiological and kinematic variables. The human body is designed for walking, and the bicycle seeks to harness this action, so a Q Factor that approaches walking step width could provide a benefit for the cyclist. The importance and use of self selected positioning on the bicycle at the pedal is likely to provide the best combination of comfort and efficiency compared with standard positioning.

6.2 Role of Q Factor in cycling

Q Factor in cycling forms part of the adjustments made to a bicycle in order to allow each individual rider to pedal with comfort and improved efficiency. Q Factor has not been explored previously in scientific research, as most focus has been upon on the two dimensional adjustments of saddle height, handlebar location and crankarm length (Barratt et al. 2011; Bisi et al. 2012; Duc et al. 2008; Fonda et al., 2011; Heil, Wilcox & Quinn 1995; Martin & Spirduso 2001; Peveler 2008; Price & Donne 1997; Umberger, Scheuchenzuber & Manos 1998; Usabiaga et al. 1997). Although the measurement has been acknowledged in the past, first known as "tread" and now "Q Factor", manufacturers and cyclists have no guidelines or recommendations as to the optimal Q Factor for their given application, both from performance and comfort perspectives.

It is critical to understand how to best optimise the cyclist's interface with the pedal. The three contact points of pedal/handlebars/saddle must be correctly adjusted for the individual cyclist, to avoid a reduction in performance or risk of injury. During the gait cycle, the human body has entirely free range of motion, apart from footstrike where the foot is in contact with the ground. Approaching the ground the foot does not have to follow a set trajectory before applying pressure and propelling the body forward, however in cycling the location of force application is fixed, and the trajectory of the lower limbs governed by the arc of the pedal. Walking gait is a relatively open system, compared to the closed system of pedalling, and thus any errors in setup that do not permit the cyclist to pedal according to their individual needs will result in a less efficient, less comfortable action.

6.3 Practical implementation of a change in Q Factor

The range of Q Factors used in this research was 90-180mm with a fixed setup, and 90-370mm using the floating pedals. 90mm was the minimum permitted by the ergometer, and any lower would be impractical to use on a mass production bicycle (or even an ergometer), due to the need for a chain drive or shaft drive system between the crank arms. A fixed maximum of 180mm may have been too low to exhibit large scale changes in muscular activity, however it was unclear what effect (if any) there would be if the participants were to use a dramatically increased fixed Q Factor >200mm. 180mm is a Q Factor found on production cranks for mountain bicycles and therefore was deemed safe to use. Many of the participants found this widest Q Factor to be uncomfortable compared with the narrower Q Factors, indicating that keeping the maximum fixed Q Factor <200mm was the correct choice. During testing in Chapter 3 23 of the 24 participants reported a dislike of Q180, and that the pedaling action felt “odd” or “uncomfortable”, preferring instead to pedal with 90 or 120mm.

Some pedal manufacturers (Look Cycle International, France; Speedplay Inc., USA; Time Sport International, France) permit the changing of pedal axle length or cleat orientation to move the foot closer to, or away from the crank arm. As previously discussed, manufacturers of crank arms are generally aware of the concept of Q Factor, but are without concise information as to the most effective Q Factors to be used. Nevertheless, road bicycle Q Factors below 150mm (Campagnolo Ultra Torque & Rotor 3D) and even below 140mm (Cannondale Si) can be achieved with production crank arms and standard bottom bracket systems – and with modification <130mm can be achieved (e.g. Shimano Dura Ace 7402 crank arms with a 102mm JIS bottom bracket at 128mm). The advent of many new bottom bracket standards in manufacturing (BB30, BB86, BB90, BBright etc.) and the integration of many frames and components (eg. Look I-Pack) permits now more than ever the possibility of narrow Q Factor bicycles for all ranges of cyclists. The effect of lower Q Factors in other modes of cycling such as maximal sprint track cycling and cross country/downhill mountain biking is also important to quantify, especially in mountain biking where Q Factors can approach 180mm. Many road bicycles have Q Factors higher than 150mm, especially entry level road bicycles, and this is increased ~20mm further with mountain bicycles. Although there are issues with crankarm clearance for mountain bicycles (largely due to increased tyre cross section and larger chainstay width), no consideration has previously been paid to attempting to reduce Q Factor on a mountain bicycle and a 20mm lower Q Factor would not be too difficult to accommodate. Even the manufacturers Walser Bicycles (Switzerland), who provide a custom narrow Q Factor crankarm and frameset combination only allow one Q Factor rather than an adjustment. A personalised bike fit should therefore include a measure of Q Factor to fit the cyclist, as such common measures as saddle height are synonymous with the idea of correct fit to the bicycle. During the experiments it was clear that many cyclists were unaware of the measurement of Q Factor, and had little understanding as to what potential benefits an optimisation could provide. The role of Q Factor when discussing bike fitting should be raised given the potential performance and kinematic improvements available to the cyclist, but of course during an holistic approach to the fit.

A reduced Q Factor should provide a benefit to the athlete, providing increased GME along with decreased lateral knee displacement.

6.4 EMG activity and metabolic improvements through a change in Q Factor

In Chapter 2 a significant increase ($p<.006$) in GME was found for 90 and 120mm Q Factor (both 19.38%) compared with 150 and 180mm (19.09% and 19.05%), however there were no concurrent changes in level or timing of activation of the four muscles analysed (vastus lateralis, vastus medialis, tibialis anterior and gastrocnemius medialis). The effective use of GME as explained previously using Douglas bags and careful analysis allows for this level of analysis, compared with e.g. the use of an online gas analyser and/or DE as a submaximal metric which would introduce error (Castronovo et al., 2013; Ettema & Loras, 2009; Hopker et al., 2011; Moseley & Jeukendrup, 2001; Moseley et al., 2004).

Previous work analysing the effect of changing stance width on muscular activation found changes during weighted squat exercise (Escamilla et al., 2001; McCaw & Melrose, 1999; Paoli et al., 2009), but there is scarce data on the effect of altered EMG activity and its relationship with GME. Previous research exploring positional changes or cadence effects has avoided the combination of GME and EMG analysis, often using either a combination of cadence and metabolic cost, cadence and EMG activity, or EMG activity and power output (Hansen & Waldeland 2008; Harnish et al., 2007; Millet et al., 2002; Neptune et al., 1997; Tanaka et al., 1996; Umberger et al., 1998; van Sickle & Hull, 2007; Welbergen & Clijsen 1990).

We would expect large scale improvements in GME based on positional changes to manifest in a reduction in EMG activity, however the improvement in GME found with the lower Q

Factors was significant but small, and so it is possible any reduction in activity was outside the signal-to-noise ratio found within the EMG system. In Chapter 4, there was no difference in self selected cadence between the four Q Factors, which may have been expected if there were substantial changes in muscular activity compared with cycling at a standard Q Factor. In addition other muscles involved in the cycling action could be responsible for the increase in GME at lower Q Factors: such as the rectus femoris, gluteus maximus and biceps femoris (Hug & Dorel 2009), and further research should explore how these may be affected with a change in Q Factor, and the subsequent effect and relationship with GME. Q Factor has not previously been explored in cycling – this research has shown that metabolic improvements are possible, even without a large change in EMG from the muscles analysed.

The improvement in GME at submaximal power outputs is shown below for various activities requiring exercise at <60% PPO. Such time savings over the course of a long distance triathlon (Ironman) or a multi-day stage race in cycling (e.g. the Tour de France) could have a measurable impact on the final result, either from allowing the cyclist to output more power for the same metabolic cost, or to output the same power, but at a reduced metabolic cost requiring less energy expenditure and therefore need for energy intake.

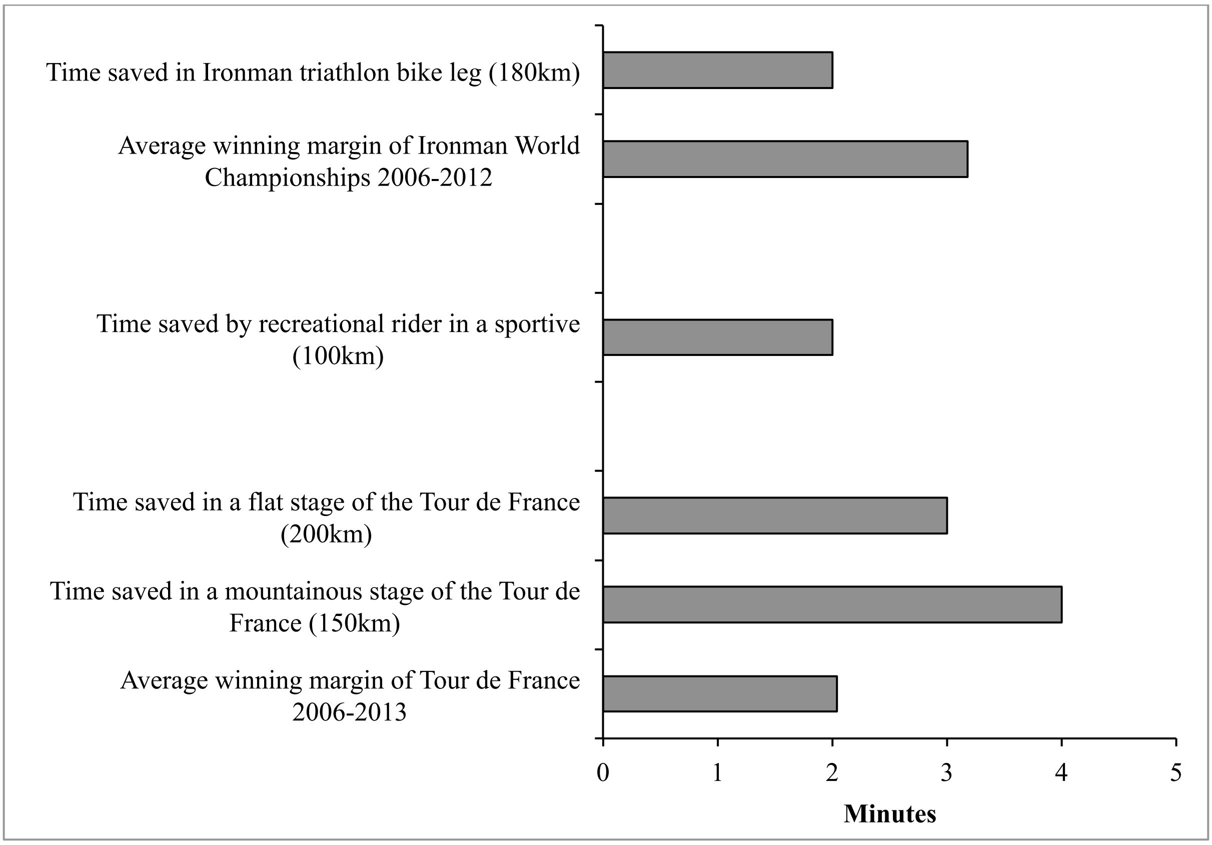

Figure 22. Time saved during submaximal (<60% VO_2max) cycling activity using narrower Q Factors than standard (<150mm).

6.5 Aerobic performance and Q Factor

In contrast to the increased GME found at low levels of aerobic cycling (60% PPO) with Q90 and Q120, there was no concurrent increase in time trial performance at ~80% PPO using Q90 and Q120, compared with Q150 and Q180. The measurement of GME is not possible at higher external workloads than ~60% PPO, as steady state would not be maintained and RER would rise above 1.0 (Hopker et al., 2011), hence the use of a performance metric such as a time trial. There is a relationship between GME and performance during time trials, however other factors such as VO_2max and lactate threshold will also affect performance (Jobson et al., 2012), and as the difference in GME was small (1.5-2% improvement in power output) then the effect of an increased GME may be outweighed by changes in VO_2max and lactate threshold. GME has also been found to decrease after a time trial (Noordhof et al., 2014), and any subsequent work exploring the interrelationship between Q Factor, GME and time trial performance could involve the analysis of GME pre and post time trial performance. The use of a 24min or 16-20km time trial is concurrent with previous research, ensuring

As has been explored in Chapter 4, there is an optimal Q Factor for each individual cyclist, the mean occurring at ~144mm, which is less than the 150mm standard found on road bicycles. Deviation from OQ caused a decrement in power output, indicating utilising OQ could provide a performance increase of 3.6% power output. The figure below shows examples of real world benefits based upon an increase in power output of 3.6% during time trial cycling.

	World Time Trial Championships 2012 (46.2km)	Olympic Games Time Trial 2012 (44.0km)	Tour de France 2012	Tour de France 2013
1st	Tony Martin (GER) 58:38.76	Bradley Wiggins (GBR) 50:39.54	Bradley Wiggins (GBR) 87:34:47	Chris Froome (GBR) 83:56:40
2nd	Taylor Phinney (USA) 58:44.13	Tony Martin (GER) 51:21.54	Chris Froome (GBR) 87:37:08	Nairo Quintana (COL) 84:01:00
3rd	Vasil Kiryienka (BLR) 60:23.75	Chris Froome (GBR) 51:47.87	Vicenzo Nibali (ITA) 87:41:06	Joaqium Rodriguez (ESP) 84:01:44
Optimised Q Factor	**- 50 sec**	**- 37 sec**	**- 1min 51sec (101.5km of time trials)**	**-57 sec (55km of time trials)**

Ultimate Hour Record

56.375km
Chris Boardman (GBR) 1996
+685m

Athlete's Hour Record

49.700km
Ondrej Sosenka (CZE) 2005
+592m

Figure 23. Time trial performance improvements using OQ.

Workloads higher than ~80% PPO (such as supramaximal sprint work) which have a contribution from anaerobic sources should also be investigated, both from a power output perspective but also as above in conjunction with EMG, as repeated sprint activity has been shown to result in a phase shift in EMG activity and a decrease in activity of relevant musculature, and altering Q Factor could have an effect in a sprint situation (O'Bryan et al., 2014).

6.6 Training status

A range of participants were involved in the research, ranging from a former national champion and national record holder, multiple regional champion and other elite riders to club rides and regular commuters. Chapter 4 utilised a highly trained subsection of cyclists, in contrast to Chapters 2, 3 and 5 which included trained cyclists (eg. VO_2max over ~55ml.kg.min^{-1}). Differences in EMG activity have been shown to be affected by training status (Hug et al, 2004; Smirmaul et al., 2010), as well as GME (Hopker et al. 2007) and research exploring the manipulation of Q Factor on an untrained population should be considered.

The 29 cyclists involved in Chapter 5 ranged from commuters who were cycling around 1 hour per week, up to elite triathletes completing 16 hours of bicycle training each week. SSQ ranged from 107-180mm, meaning that no cyclist self selected a Q Factor above which they may have been exposed to during their training/riding on a standard bicycle. Given that some of the participants in this study rode more than one bicycle (eg. race vs. training bicycle, mountain vs. road bicycle), and for varying amounts of time during their weekly activity, it was not possible to measure a Q Factor that was most used by the cyclists without some level of error. In addition, the use of different pedal axle lengths and pedal cleats (as well as location of the cleats) would have added to this error – the Q Factor in this study was measured to a fixed point on the floating pedals, so the Q Factors were more relevant than a simple bike-to-bike comparison.

However, it is less likely that the commuter cyclists would ever have been exposed to the low Q Factor of a high end road racing bicycle, and the converse is true for the elite cyclists/triathletes.

Subject no.	18	5	6		28	30	26
Weekly hours	1	1	1		14	15	16
SSQ (mm)	147.33	159.93	165.75		146.66	141.00	153.47

Table 8. Cyclists with the highest and lowest amount of weekly training and SSQ in the Free condition.

The three cyclists with the highest number of training hours had a similar or lower Q Factor than standard road bicycles, whereas the three cyclists who only trained for one hour per week tended towards higher Q Factors. We would expect that exposure to higher Q Factors would cause a rider to self select that Q Factor, especially in an acute condition, and this raises the question of whether training at a lower Q Factor would reduce SSQ, and for how long a training period would be required. If the commuter cyclists at the lower end of the training scale self select a higher Q Factor on only 1 hour of riding per week, it suggests that it may not take that long to become accustomed to. In the same way that body position and training status has an effect on muscular recruitment during cycling (Ashe et al., 2003;

Chapman et al., 2008) training with different Q Factors could result in changes in muscular recruitment, and also GME.

6.7 Repeatability of measurements

As has been discussed previously, GME is less variable than DE and is unaffected by circadian rhythm (Moseley & Jeukendrup, 2001; Moseley et al., 2004; Noordhof et al., 2010). Nevertheless in Chapter 2, 3 and 4 all tests were completed at the same time of day and diet was replicated before each trial to remove the impact of e.g. carbohydrate intake on GME (Cole et al., 2014).

A repeat trial in Chapter 5 was conducted in order to explore whether SSQ would be consistent between trials on separate days – no differences were found in SSQ with a CV of <5% which implies that it is a repeatable process to conduct acutely in the laboratory. Any changes in SSQ discussed in Chapter 3, as a result of training, would therefore need to involve cycling for more than twice per week for the short periods of time used in this experiment. From Chapter 3 we can estimate that 1 hour per week may well be sufficient to elicit a change in SSQ but this warrants further study. The use of randomisation compared with counterbalancing in the above studies may cause an order effect, and subsequent work can address this with counterbalanced trials using a change in Q Factor.

6.8 Walking and range of Q Factors whilst cycling

As walking is largely a submaximal activity, we can draw a comparison between walking economy and the GME of submaximal cycling <60% VO_2 max. The most efficient Q Factors were 90 and 120mm for trained cyclists of either sex compared with higher Q Factors >150mm, which is similar to the 100-130mm range found during walking. Although in Chapter 2 the major cycling muscles analysed (gastrocnemius, vastus medialis, vastus lateralis, tibialis anterior) did not show changes in timing of level of muscular activity, there are other crossover muscles used in both cycling and the gait cycle, such as the rectus femoris and biceps femoris, as well as lateral stabilising muscles such as the adductor longus and tensor fasciae latae. A reduction in the activity and subsequent oxygen consumption of the muscle would result in a greater GME. Chapter 4 also showed that on average <150mm was optimal, even at a higher % of the VO_2max and moving away from submaximal activity. The use of pedals instrumented with force sensors would determine any force effects by changing the Q Factor and whether the angle of force application was improved (ie. less tangential force applied during the pedal stroke).

In Chapter 3 the range of Q Factor available using the custom pedals was from 90-370mm, and it was only when the cyclists were allowed full range of motion (rather than just lateral movement) that individual differences in Q Factor appeared. During walking there is complete freedom of movement during the gait cycle, and here the more experienced cyclists explored their degrees of freedom in order to find their SSQ (137mm). The less experienced cyclists self selected a Q Factor (153mm) that was very close to the 150mm of a standard road bicycle, which suggests that they have less ability to explore their degrees of freedom, instead self selecting close to standard.

6.9 Individual gait

In Chapter 5 the relationship between individual gait characteristics and SSQ again found that mean SSQ was lower than 150mm at 142mm, but that stepping and walking tasks did not predict SSQ. Kinematic analysis of the cyclists walking a distance of 6m before stepping onto a box 15cm in height provided no relationship between walking step width or static step width (once stationary on the box) and individual SSQ. Instead a hanging test, where the participants suspended themselves in the gymnastic support position had a strong correlation with SSQ ($R^2=0.794$, $p<.002$). The Y intercept of the equation for this relationship ($y = 0.5692x + 114.74$) implies a minimum SSQ of ~ 115 mm – in Chapter 3 the two lowest SSQ's from all the participants were 107 and 113mm, and in Chapter 5 the lowest SSQ was 120mm. It is likely that, in the same way that walking step width causes an increase in economy when it goes too low, minimum SSQ would be centered around 115mm and not below 100mm. A low Q Factor of 90mm as found in Chapter 2 may result in high gross mechanical efficiency, but perhaps at the cost of comfort. The effect of knee kinematics on injury potential is difficult to analyse in the laboratory, given the ethical constraints of allowing cyclists the risk of becoming injured.

6.10 Moving away from SSQ

The importance of SSQ is further highlighted when examining kinematic variability at the knee in Chapter 5. Although there was only a small difference in GME between the Q150 condition and SSQ (142mm), knee stability increased by nearly 3% when using SSQ compared with Q150 as well as the increased GME. Moving 30mm higher or lower from

SSQ saw a reduction in GME of ~1.5% combined with a decrease in knee stability of ~3.5%, which follows the reduction in time trial performance of 3.6% found in Chapter 4, when Q Factor was changed 22mm from OQ (144mm).

6.11 Individual characteristics and predictors

The human body has evolved to be economical at walking, and the basis for lower Q Factors than are found on standard bicycles and individual position stems from an unique adaptation to walking. Individual morphology will determine the exact Q Factor required for performance and comfort, and SSQ results in less kinematic variability during the pedal stroke as well as increased GME. It is interesting that the best predictor of SSQ was a hanging task, where the legs were suspended and completely free to move, compared with a stepping activity where perhaps the precision of the task (walk 6 metres and then accurately step onto a box) prevented the cyclists from exploring free range of motion, compared with walking or running on a large treadmill or open space. However, the ease of using a hanging task to determine SSQ would make it more simple to execute for the end user cyclist.

6.12 Further work

The present work has examined a concept that has not previously been explored in scientific research. Q Factor has been shown to have an effect upon metabolic and kinematic variables in cycling, over a range of trained cyclists and at low and high aerobic power outputs. Q Factor is an important adjustment to the bicycle that should be considered alongside measurements such as crank length and saddle height. However, it is beyond the scope of this research to cover all possible effects of Q Factor on cycling performance and kinematics. In particular, further work should explore the role of muscles such as the gluteus maximus and biceps femoris and their recruitment during the pedalling stroke when Q Factor is manipulated, as the vastus lateralis and vastus medialis were found to be unaffected at submaximal power outputs in Chapter 2 in contrast to the original hypothesis. In addition, Q Factor may have an effect on EMG activity whilst fatigued, both at submaximal, maximal aerobic and supramaximal sprint cycling. Any large adjustment of Q Factor (ie. >30mm away from SSQ) at power outputs greater than PPO should be treated with caution, as the forces involved are increased dramatically during sprint cycling. Finally, this research was conducted with a standard upright position on the bicycle – narrowing the Q Factor may have a beneficial effect upon aerodynamics as previously discussed and so aerodynamic measurements should be explored as well any potential change in SSQ or OQ as a result of adopting an aerodynamic position.

6.13 Conclusions

The human body is designed for locomotive action, both walking and running. Bicycles were first designed to harness this action and provide a faster mode of transport, and later into competitive sport. Technological advances have continued the evolution of the bicycle, and in recent years the widespread use of clipless pedals for all forms of cycling have increased the importance of correctly positioning the rider onto the pedals.

In this thesis, we have seen that lower Q Factors than the standard 150mm for road bicycles provide performance and kinematic benefits that have not been examined previously. As part of the overall package of bicycle fit, individual cyclists will be able to make measurable improvements by finding and utilising their self selected Q Factor.

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