

EFFECTS OF A BI-DIRECTIONAL PEDAL PATTERN ON FATIGUE IN CYCLING

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Abstract

The purpose of this study was to investigate the effects of a bi-directional pedal pattern (a combination of forward and backward pedaling), on the process of fatigue in cycling. Thirty-three subjects participated in this study (18 trained, age 31.4 ± 11.1 years, average 9.6 ± 9.7 years training; 15 untrained, age 28.6 ± 11.3 years). Subjects participated in four sessions on different days: a maximum sustained power test, followed by three tests to voluntary fatigue for each of these randomly assigned pedal patterns (forward only, backward only and a bi-directional (BI)). Heart rate and blood lactate measured the intensity of exercise. Kinetic, kinematic and EMG data quantified the fatigue process. Main results show that the BI pedal pattern delayed the onset of fatigue in untrained subjects. Future research should explore the BI pedal pattern after subjects train in backward pedaling, as well as the optimal forward to backward pedaling ratio for the BI pedal pattern.

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List of Abbreviations

- BI – bi-directional
- BF – biceps femoris
- BL – blood lactate
- BO – backward only
- bpm – beats per minute
- EMG – electromyography
- EOC – energetically optimal cadence
- FCC – freely chosen cadence
- FO – forward only
- GE – gross efficiency
- GL – gastrocnemius lateralis
- GM – gastrocnemius medialis
- HR – heart rate
- NOC – neuromuscular optimal cadence
- MOC – metabolic optimal cadence
- MPF – median power frequency
- PO – power output
- RF – rectus femoris
- ROM – range of motion
- ROP – range of position
- SM – semimembranosus
- SOL – soleus
- SPO – sustained maximum power output

ST - semitendinosus

TA – tibialis anterior

VI – vastus intermedius

VL – vastus lateralis

VM – vastus medialis

Chapter 1 – Introduction

Purpose of the study

The purpose of this study is to determine the mechanical efficiency of a new bicycle design: a bi-directional bicycle. This type of bicycle allows a person to pedal in either the forward or backward direction to create forward propulsion. Innovations in bicycle design are generally geared toward making bicycles more efficient or allowing the cyclist to make optimal use of their energy expenditure in order to get from one place to another, whether using the bicycle as a means of transportation or in sport. This design is no exception. In this investigation, I examine both biomechanical as well as physiological parameters that may be influenced by this new design.

As is generally known, most bicycles are designed such that the act of pedaling in the forward direction causes the bicycle to move forward, while pedaling in the backward direction does not result in any kind of power transfer from the cyclist to the bicycle. Thus, because of frictional forces (excluding factors such as hills or tail winds) pedaling in the backward direction on a traditional bicycle design will result in a loss of forward momentum. Cyclists on these kinds of bicycles have to pedal in the forward direction at some point, or they will eventually come to a stop. At best, pedaling in a backward direction might provide an opportunity for a cyclist to “spin out” his or her legs, effectively resting them by temporarily changing their muscle control pattern.

Other bicycles allow an individual to move forward by pedaling forwards and to move backward by pedaling backwards. These are called fixed-gear bicycles. While pedaling in either direction, the cyclist encounters resistance, the overcoming of which generates power that is transferred into the movement of the bicycle and the cyclist. As

an individual pedals on this type of bicycle, because the gear is fixed to the wheel, the bicycle will move in the direction that the rider pedals (forward or backward) and at a speed that is directly proportional to the speed of pedaling. Since the wheels move as a direct result of the pedal movement, a fixed-gear bicycle is not able to coast; if the wheels are moving, so too are the pedals. Pedaling on this type of bicycle must be continuous in order for movement to occur.

This research project employs a new bicycle design that allows a cyclist to generate forward movement of the bicycle by pedaling in either the forward or the backward direction. Further, the design permits the cyclist to switch directions at will, seamlessly maintaining forward propulsion of the bicycle. The goal of this research is to investigate the efficiency of the new bicycle design with a pedal pattern where the rider switches between pedaling forward and backward, measuring both physiological measures as well as biomechanical measures, to see if this new pedal pattern is able to delay the onset of rider fatigue. To do so, it was necessary to design a protocol that evaluated the design of the bicycle as well as the biomechanical and physiological effects of pedaling on the rider.

In order to evaluate the mechanical effectiveness of this new bicycle design, a preliminary study compared the efficiency of backward pedaling to that of forward pedaling. The preliminary study also permitted the evaluation of the mechanical effectiveness of the new bicycle design by comparing it to a fixed-gear bicycle.

Theoretically, a fixed-gear bicycle should be highly efficient with regard to energy transfer from the cyclist to the bicycle because of its minimalistic mechanism. Using a

fixed-gear bicycle as a benchmark for comparison, I found that, on average, maximum sustained power on the new bicycle was approximately 83% of that sustained on the fixed-gear bicycle.

To evaluate the biomechanical and physiological effects on the rider from pedaling forwards and backwards, subjects were asked to pedal on a bicycle mounted to an indoor trainer until they reached voluntary fatigue. Parameters measured and investigated include: pedal force, joint angles, muscle activation levels, heart rate (HR), blood lactate levels (BL), and time. These parameters were compared between three different pedal patterns: 1) Forward only (FO), 2) Backward only (BO) and 3) Bi-directional (BI), a combination of forward and backward pedaling.

Significance

To date, very little research has been done on backward pedaling. The literature that I have found have mostly investigated backward pedaling as a method of rehabilitation for individuals who have experienced knee injuries. To the best of my knowledge, there is no research to date looking at the efficiency of pedaling in the backwards direction for the purpose of generating forward momentum during cycling. Additionally there has been no research examining any effects of alternating pedal direction. Additional research is needed to examine these relationships in order to find the most efficient pedal pattern.

This study will compare the onset of muscle fatigue for the traditional FO pedaling pattern to the BO and BI pedaling patterns. This is important because delaying muscle fatigue allows a person to cycle for a longer period of time before exhaustion occurs. The

BO pedal pattern was examined in order to provide a comparison for the backward portion of the BI condition.

Hypothesis

I hypothesize that bidirectional pedal configuration (BI) of the newly designed bicycle will permit cyclists to better maintain the desired pedaling cadence and level of power output (PO) than for either the forward only (FO) or backward only (BO) pedaling patterns.

Chapter 2 – Review of the Literature

Efficiency in cycling can be defined in a number of ways. Essentially, efficiency refers to how effectively mechanical energy from the rider is transferred into power to propel the bicycle forward. In a review of the literature, Ettema and Loras (2009) stated that they were unable to make any firm conclusions about the efficiency of cycling because multiple factors affect energy expenditure. In cycling, many of these factors are inter- or co-dependent, so it is very difficult to pinpoint the effect of just one factor (Ettema & Loras, 2009).

Despite Ettema and Loras's conclusion, several factors have been extensively researched with regard to their contribution toward the optimization of gross efficiency in cycling. These studies provided a foundation for my thesis. Areas of research examining gross efficiency can be grouped into the following categories: 1) equipment and ergonomics, 2) cycling technique, 3) physiological factors, and 4) physical conditions. Although, some of the above are more relevant than others in their contribution to my research, aspects of all have influenced my research design. A literature review will be provided for all of the categories above. Those which are most influential for my thesis will be documented in detail while those that contribute less will be treated summarily. Finally, the 5th section of this literature review documents procedures directly related to my experimental design including 3-D motion capture as well as pedal force measurements, since they are essential technologies employed in this thesis.

Equipment and ergonomics

When investigating equipment that a rider uses, researchers extensively examine the bicycle and any external gear that the rider requires, including: materials used for construction, componentry of the bicycle, clothing, shoes and helmets. The goal of such research typically concentrates on minimizing weight in order to decrease the force required to move the bicycle and/or decrease the effects of ground friction. Equipment weight can have dramatic effects in terms of rider fatigue. At the same time, research also studies ways to maximize aerodynamic properties of both the bicycle and the rider in order to decrease friction due to air resistance and turbulence. The vast majority of this research is devoted to cycling as a sport. In a sporting environment, any equipment allowing better mechanical efficiency can reduce the time to the onset of fatigue for a cyclist. In the case of elite athletes, energy conserved by any measure can lead to improvement in overall performance (G. Millet, Perrey, Divert, & Foissac, 2006).

In terms of minimizing the weight of bicycles, materials used to construct frames has been a primary concern; they have changed dramatically during the 20th century. Steel frames, popular in the first part of the century, were strong but heavy. As new materials became available, manufacturers started making frames from aluminum because it is a lighter metal, even though it resulted in slightly weaker frames. Other materials such as chromoly, an alloy of steel, chromium and molybdenum were used to achieve a compromise between the strength of steel and the lightness of aluminum. Being both strong and light, titanium has also been used for bicycle frames. Unfortunately its cost is prohibitive. More recently, carbon fibre has been employed in the construction of bicycle frames. Dramatically reducing the weight of frames, carbon fibre is not as strong

as the metals identified above and is prone to critical damage when its relatively low stress tolerances are surpassed. Currently, it remains a material of choice because it has the advantage of being easily shaped or moulded and, as a result, the frame can more easily be made more aerodynamic than those constructed from traditional alloys.

Components of bicycles such as derailleurs, crank-sets, chain-rings, as well as gear and brake levers are also subject to redesign in order to incorporate the latest technology to improve cycling performance. Some of the outcomes of these alterations include faster and smoother shifting, decreased time spent in transition between gears and reduced mechanical friction as the rider changes gears. Theoretically, minimizing the amount of friction or other mechanical inefficiencies in these contexts maximizes energy transfer from the rider to the bicycle.

However, newer and better component technologies don't always prove to be mechanically advantageous. A study by Belen, Habrard, Micallef, and Le Gallais (2007) compared a carbon chain-ring to a standard metallic chain-ring. They found that the carbon chain-ring did not actually deliver the anticipated mechanical advantage over the standard metallic chain-ring. Their method involved assessed cyclists' levels of exertion by measuring oxygen consumption, carbon dioxide production and BL levels. Compared to the metal chain-ring, results from the trials using the carbon chain-ring showed higher levels of oxygen consumption and carbon dioxide production, with no noticeable difference in BL. Such results indicated reduced efficiency.

Aerodynamics research designed to decrease air resistance of both the bicycle and the rider is also used to improve efficiency in cycling. Cyclists are always looking for

ways to improve their ability to become more aerodynamic, thus limiting the effect of air resistance (I. E. Faria, 1992). In addition to the above mentioned use of materials as a means to improve aerodynamics, bicycle design and geometry is another active area of research that investigating air resistance. Capelli et al. (1993) examined bicycles specifically designed to minimize air resistance while cycling. According to their results, when riding these bicycles, cyclists could expect a three percent improvement in performance.

Another area of research that influences aerodynamics is a rider's position. This has been extensively researched. A cyclist's position on the bicycle is influenced by multiple factors including bicycle set-up, the style of handlebars, frame geometry, tube angles, seat height, seat tilt, stem length and crank arm length. Experiments adjusting these parameters typically aim to lengthen and flatten the rider's body in order to increase aerodynamic properties while maintaining a rider posture (i.e joint angles of the limbs) that will allow for optimal transfer of power through the drive train. For example, Sheel, Lama, Potvin, Coutts, and McKenzie (1996) found energy savings by using aero bars which caused riders to lengthen body position and compress arms and hands toward the midline of the bicycle. In a separate study, it was observed that aerobars changed the angle of a rider's trunk, resulting in both altered muscle recruitment patterns and joint angles for all joints of the lower extremities with the exception of the knee (Savelberg, Van de Port, & Willems, 2003). Some of the effects observed from the use of aerobars can equally be achieved by altering other geometric features of the bicycle, such as seat height and placement (the horizontal movement of the seat above the seat-post).

Seat height has been investigated by a number of researchers. Rodrigo R. Bini, Tamborindeguy, and Mota (2010) investigated the effect of seat height on lower extremity kinematics. They found that higher seat positioning required increased contribution from the ankle joint, while a lower seat positioning resulted in increased contributions from the knee. In turn, such motor pattern differentials affect the way the muscles are used, which may increase chances of soft tissue injuries. Another investigation of seat height reported that a lower seat height to result in a lower level of activation of the soleus and the gastrocnemius medialis, two muscles that contribute substantially to power generation (Sanderson & Amoroso, 2009). Diefenthaler, Bini, Barcellos Karolczak, and Carpes (2008) also investigated the effect of seat placement adjusting the seat in three ways: height, tilt and horizontal placement (forward, middle back). They found that minor adjustments in the placement of the seat influencing a rider's rate to fatigue by affected pedaling technique and muscle activation patterns.

Crank arm length was investigated by J. C. Martin and Spirduso (2001). They found that, not only was maximum cycling power significantly affected by crank length, different crank lengths also had different optimal cadences in order to produce maximum power output. Morris (1992) found that optimal crank arm length is specific to the individual (in order to maximize efficiency of cycling). However, they were not able to correlate optimal crank arm length to subjects' leg length.

Cyclists are often adjusting their position in order to find a position that will optimize both aerodynamics and the efficiency of power transfer. The amount of power a cyclist is able to generate seems to correlate with cycling success (E. W. Faria, Parker, & Fria, 2005). As a means of maximizing power, most cyclists use shoes that clip into

special pedals (toe clips) so that the pedal (and thus the crank arm) effectively function as an additional segment of the leg. Although the maximum velocity of pedal rotation was not found to be affected by the use of toe clips, maximal power output was found to be significantly higher (Capmal & Vandewalle, 1997). Capmal and Vandewalle attributed increase in power production to the cyclist's ability to pull upward on the upward phase of the pedal stroke.

Pedals are not the only aspect of a bicycle that influences power in the pedal stroke. A study by de Groot, Welbergen, Clijisen, and Clarijs (1994) confirmed that maximum power is influenced by body position. Notably, the position that is most aerodynamic is not necessarily the best position to generate maximal pedaling power. Standing vs. sitting while cycling, on both flat surfaces as well as on hill climbs, was investigated by G. P. Millet, Tronche, Fuster, and Candau (2002). They found that there were no significant long-term differences in efficiency between the seated and standing positions for either condition, however they did determine that greater short-term power is produced in a standing position. They suggested that this greater power output was a result of greater force output during pedal revolution, but this did not affect the long-term overall efficiency.

Seat tube angle has also been shown to influence the power output and efficiency in cycling (Price & Donne, 1997). Hip range of movement and maximum and minimum hip angle were significantly less with a seat tube angle of 80° compared with 68°. Further biomechanical analysis suggested that improvement in cycling efficiency observed at steeper seat tube angles was produced in part by the resultant altered pattern of the ankle in the pedal stroke. Rankin and Neptune (2010) investigated the effect of seat tube angle

on crank power, and they found that the seat tube angle had little influence on crank power, with maximal values varying at most by one percent across a wide range of seat tube angles.

Cycling technique

Power, cadence and cycling economy have a complex relationship. There does not seem to be consensus in the literature as to how they influence or affect one another. Cadence (or pedal rate) refers to the number of pedal revolutions occurring per minute of pedaling. Several research projects have been devoted to attempting to find an optimal cadence for cycling efficiency. It should be noted that “optimal cadence” can be classified differently depending on the underlying assumptions of the researchers. For example, an energetically optimal cadence (EOC) defines “optimal” in terms of energy conservation; conserved energy results in increased endurance of a cyclist. A freely chosen cadence (FCC) is the cadence that the cyclist chooses. Other definitions included neuromuscular and metabolic optimal cadences (NOC and MOC respectively). In the paragraph immediately below a sampling of this extensive literature is provided to lay groundwork for my experimental design.

Conflicting research results have been documented in the literature examining optimal cadence. This is primarily due to inconsistent definition of the term. "Optimal cadence" has been used to describe energetic cost, muscular stress, and perception of effort, among others. The issue of optimal cadence is further confounded by the intention of power generation – that is, at higher power outputs, the optimized cadence is different from that at lower power outputs (Ansley & Cangle, 2009). This suggests that cadence affects power, not cycling economy. In an earlier study Marsh, Martin, and Foley (2000)

also found that cadence did not significantly affect cycling efficiency. In a study examining the relationship of cadence to power output and efficiency, Mora-Rodriguez and Aguado-Jimenez (2006) found that Gross efficiency (GE) did not differ among trials at three different cadences (80, 100, 120 rpm), but that power output increased at a cadence of 120 rpm. This seems to reinforce the findings of Ansley & Cangle (2009), that power is actually influenced high cadence, but cadence did not necessarily influence overall economy. Marsh and Martin (1997) also found that changes in power output had little effect on the most economical cadence. In a seemingly contradictory finding, Foss and Hallen (2004) asserted that the most economical cadence actually increased as workload increased. This outcome was supported by findings of Samozino, Horvais, and Hintzy (2006) where cadences producing optimal gross efficiency at different power outputs were examined. They found that, as power output increased, gross efficiency increased independently of cadence. Hence, as power output increases, the effect of the cadence on overall efficiency in cycling is minimal. The findings of all the above appear to agree that cadence does not actually affect the gross economy in cycling.

However, findings by Woolford et al. (1999) emphasised that pedal cadence specificity is essential when assessing cycling economy, and Chavarren and Calbet (1999) found that the effect of pedaling cadence on general economy decreased as a linear function of power output. Abbiss, Peiffer, and Laursen (2009) determined that lower cadences (70-90 rpm as opposed to 90-100 rpm) improved cycling efficiency in ultra-endurance cycling (>4 hours). However, they noted that cycling at a lower cadence required a higher gear ratio in order to produce the same amount of power in the cycle.

Several studies compare freely chosen cadence (FCC) to “optimal” cadence. While differing in choice of definition for “optimal,” they found that experienced riders tended to choose cadences close to the energetically optimal cadence (EOC) (Brisswalter, Hausswirth, Smith, Vercruyssen, & Vallier, 2000). FCC has been reported to be close to EOC for endurance athletes, which suggests that there may be a training effect on the muscular adaptations. These adaptations in turn influence the FCC (Vercruyssen & Brisswalter, 2010). Bieuzen, Vercruyssen, Hausswirth, and Brisswalter (2007) found that, in sub-maximal cycling, EOC and NOC were significantly related to the strength of the rider, while NOC and FCC were more closely related to endurance training, supporting the theory of the training effect.

Some studies seem to conclude that higher cadences are more economical while others identify lower cadences to be more economical. Belli and Hintzy (2002) found the EOC to be between 90 and 110 rpm, a high cadence. Similarly, Lucia et al. (2004) found that in professional cyclists, lower pedaling cadences (60 rpm) are less efficient than higher pedaling cadences (100 rpm). Dantas et al. (2009) found both pedaling economy and muscle recruitment to be improved at higher cadences in both trained and untrained cyclists.

However, Ganzit, Talpo, Fontana, Gottero, and Valente (1999) found the contrary to be true. They found optimum cadence resulting in maximum power during aerobic conditions to be lower than the FCC. In an investigation examining a number of different pedal rates, Coast, Cox, and Welch (1986) found gross efficiency, heart rate, and perceived exertion all to be minimal at 60 or 80 rpm. Other studies confirm cadences

around 80 rpm to result in a better work economy (Foss & Hallen, 2004; Hansen, Andersen, Nielsen, & Sjogaard, 2002).

The existence of a large variety of explanations for why one or another cadence proves to be “optimal” is demonstrated by the following selected examples of research. Brisswalter et al. (2000) suggested that duration of exercise influences the optimal cadence and higher cadence is better for longer durations of pedaling. He explained this shift to result from muscle fibre recruitment pattern. Hintzy, Belli, Grappe, and Rouillon (1999) conducted a study looking at cadence in both maximal and sub-maximal cycling exercises. In this study, they found that optimal pedal velocity during a maximal test to be much higher than optimal pedal velocity during a submaximal power test (123.1 ± 11.2 rpm vs. 57.0 ± 4.9 rpm respectively). In looking at the cadences of both endurance athletes and explosive athletes (participating in anaerobic exercise) in conditions of maximal and submaximal cycling, they concluded that distribution of muscle fibre type (slow or fast-twitch) actually affects optimization of cycling. Results from other studies support these findings; muscle fibre types influencing the efficiency of cycling at differing pedal rates (Abbiss et al., 2009; Ansley & Cangle, 2009; Hansen & Sjogaard, 2007; Hintzy et al., 1999). Hansen and Sjogaard (2007) found that increasing pedal rate increases power output but is not directly related to overall efficiency. They concluded that the percentage of slow twitch muscle fibres contributes to this finding. In terms of pedaling technique Rossato, Bini, Carpes, Diefenthaler, & Moro, (2008) investigated pedal rate by dividing rotation into two phases; propulsion and recovery. FCC was determined to be the best technique during the propulsive phase while lower cadences were more effective during recovery.

Muscle activity

Cadence has also been linked with muscle coordination and activation during the pedal stroke. Muscle contributions to pedaling have been identified as falling into three general categories (Neptune, 2000; C. Raasch & Zajac, 1999; Ting, Kautz, Brown, & Zajac, 1999). These groups are categorized as follows: flexors & extensors (moves the limb in flexion or extension), plantar flexion & dorsiflexion (moves the foot in plantar flexion or dorsiflexion), and anterior & posterior movement (moves the foot anteriorly or posteriorly in reference to the pelvis).

Bieuzen, Vercruyssen, et al. (2007) found that cadence influenced lower extremity muscle activation levels. They reported that, at higher cadences, the BF and RF activation started earlier in the pedaling cycle. Sanderson, Martin, Honeyman, and Keefer (2006) investigated the effect of cadence on the soleus and gastrocnemius muscles. They found that the activation level of the gastrocnemius increased with a higher cadence, and cadence had no significant effect on activation levels of the soleus. The ankle became more plantar flexed and had a smaller range of motion (ROM) and the knee was less extended at higher cadences.

Other studies have been conducted investigating the role of the leg muscles in cycling (Rodrigo R. Bini, Carpes, Diefenthaler, Mota, & Guimaraes, 2008; Dorel et al., 2010; Morris, 1992; Sanderson et al., 2006). Each of these sources discusses muscle contributions to phases of pedaling. Dorel et al. (2010) defined four different phases: top (330° - 30°), downstroke (30° - 150°), bottom (150° - 210°), and upstroke (210° - 330°) where 0° is the 12 o'clock position. Specific muscles dominated movement during each phase of pedaling. Lower limb flexor muscles (biceps femoris (BF), semimembranosus

(SM), semitendinosus (ST)) pull on the pedal during the upstroke (recovery phase) while quadriceps (vastus lateralis (VL), vastus medialis (VM), vastus intermedius (VI), and rectus femoris (RF)) and gluteal muscles (gluteus maximus, gluteus medius, gluteus minimus) are primarily responsible for the down stroke (power phase). The gastrocnemius medialis (GM), gastrocnemius lateralis (GL) and soleus (SOL) muscles are primarily responsible for the bottom part of the stroke, while the hip flexors and gluteal muscles are responsible for the top part of the stroke (see Figure 1).

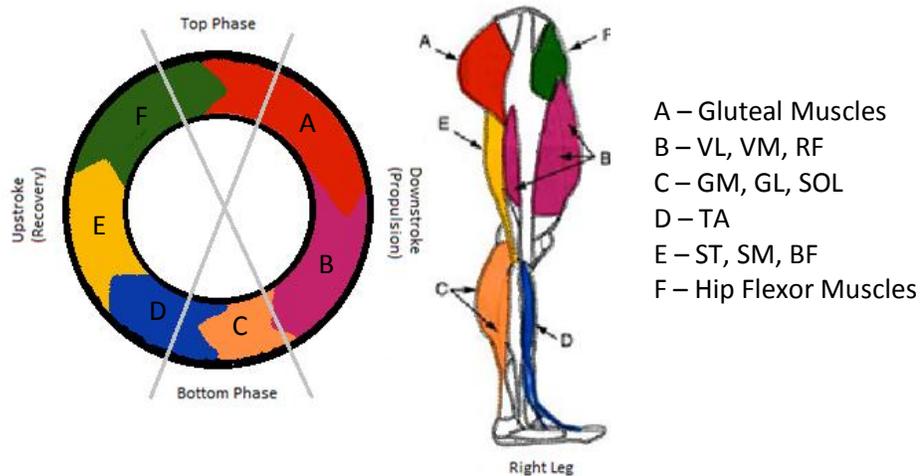


Figure 1 - A diagram outlining the phases of the pedal stroke with location of main accompanying muscle contributions. (Image adapted from BikeJames.com Wilson (2012)).

Each muscle in the leg has a specific period of activation within a pedal stroke and plays a specific role in the movement of the pedal. For example, the SOL is responsible for the initial propulsive force (part of the bottom phase of the stroke) and the GL works synergistically with the GM but places continual force on the pedal (Rodrigo R. Bini et al., 2008; Sanderson et al., 2006). Gluteus maximus, SOL, RF and VL are responsible for

placing force on the downstroke (Rodrigo R. Bini et al., 2008; Neptune, 2000). Hip extensors work synergistically with the TA, while the VM, VL and hamstrings functioned independently to accelerate the crank in the bottom phase. Rodrigo R. Bini et al. (2008) also reported that the BF and RF are closely related to the pedaling technique.

Results from another study concluded that introducing more dorsiflexion into the pedal stroke of a trained cyclist increases muscle activity of the GL (Cannon, Kolkhorst, & Cipriani, 2007). They found that this decreased GE when compared to the self-selected pedal stroke, suggesting that biomechanical and kinematic changes affect the muscle recruitment pattern. This conclusion is supported by another study that altered trunk angles. Using EMG, (Savelberg et al., 2003) found that altering trunk angles affected all of the muscles that act on the hip joint with respect to timing and magnitude of activation.

Chapman, Vicenzino, Blanch, and Hodges (2008) found muscle recruitment to vary according to cycling experience. They suggested that the highly trained cyclists' muscle recruitment patterns are more refined than those of untrained cyclists, a result due to repetition involved during training and competition. They also suggested in a later study that differences in leg muscle recruitment between novice and elite cyclists may be explained in part by small kinematic variations at the ankle (Chapman, Vicenzino, Blanch, & Hodges, 2009).

Knowledge of muscle recruitment throughout the pedal cycle has important implications for training and body position adjustments (E. W. Faria et al., 2005). With this knowledge, cyclists can focus on muscle strengthening and recruitment of muscles while they are training, which may in turn increase their power output and increase their

efficiency. J. G. Hopker, Coleman, and Wiles (2007) also found that efficiency differences do exist between trained and untrained subjects.

Contrary to the conclusions in some of these studies, other researchers claim that trained cyclists are actually no more efficient than untrained ones. A study investigating preferred cadence in highly fit athletes found that cycling experience did not influence either cadence or cycling economy during moderate intensity cycling (Marsh & Martin, 1993). A later study conducted by Marsh et al. (2000) found that cycling efficiency was not found to differ according to cycling experience or fitness level of the subject. Similarly, Moseley, Achten, Martin, and Jeukendrup (2004) investigated trained world-class cyclists and compared their efficiency to that of recreational cyclists. They also concluded that cycling efficiency was not dependent upon cycling experience.

Despite the disagreement of sources with regard to the effects of training on efficiency, certain aspects of cycling may be attributed to experience. Atkinson, Davison, Jeukendrup, and Passfield (2003) suggested that cyclists could use pacing strategies to conserve energy. These strategies include increasing power in headwinds and for hill climbing as well as decreasing power in tailwinds and for hill descending. These experience-dependent strategies are intended to delay the onset of fatigue.

It has been reported that muscle fatigue in the lower body alters cycling motion and muscle activation patterns (So, Ng, & Ng, 2005). Biomechanical measurements are one means to measure muscle fatigue (Haapala, Faghri, & Adams, 2008). Lattanzio, Petrella, Sproule, and Fowler (1997) found knee and ankle joint ROMs to be affected by the onset of fatigue. Contrastingly, Lepers, Millet, and Maffiuletti (2004) found that, despite the

fact that muscles became fatigued, pedal control remained consistent until exhaustion was reached.

Fatigue also affects muscle recruitment patterns. Dorel, Drouet, Couturier, Champoux, and Hug (2009) found that there was a forward phase shift in the GM, GL, TA, VL, VM and RF as muscles fatigued, while the gluteus maximus and BF increased in activity. They suggested this increase of activation levels to be a subconscious strategy to compensate for fatigued muscles, specifically the VL and VM. Contradictorily, Rodrigo R. Bini et al. (2008) found that the GM, GL or the BF were not affected by fatigue.

Physiological parameters

Two physiological parameters are often used in studies investigating exercise and fatigue. Heart rate is generally used as a measure of exercise intensity. One of several theories regarding fatigue identifies lactate build-up in the blood system as a cause of muscle fatigue.

A linear relationship exists between exercise intensity and heart rate – the more intense the exercise, the higher the heart rate. However, heart rate plateaus as fatigue is approached (Bozeman, 1998). In terms of cycling, one study concluded that cadence did not actually have a direct influence on heart rate (Chavarren & Calbet, 1999). A cycling study linking heart rate to age and blood lactate levels found age to have more of an effect on heart rate than lactate levels (Balmer, Bird, Davison, & Lucia, 2008).

Blood lactate levels (BL) have been successfully used as an indicator of fatigue for many different sports. No significant gender-related, BL differences (expressed as a percentage of VO_2 max) were found in runners (Iowaka, Hatta, Atomi, & Miyashita,

1998). Similar results have been found in swimming. Higher age groups, regardless of gender, tended to have higher lactate levels, suggesting that age has more of an effect on lactate levels than exercise intensity. Older subjects tend to build up lactate levels quicker (or remove lactate less efficiently) than younger subjects during exercise (Avlonitou, 1996). Another study looked specifically at the response of BL in males aged 20-80 (Tzankoff & Norris, 1979). They found that, as males age the ability to diffuse lactate from their muscles decreases, resulting in a decrease in endurance and longer recovery after exertion. They also reported that, during exercise, lactate levels increased much more rapidly in the 70+ age group, and only slightly more rapidly in the 50-70 year age groups than for those younger than 50. Balmer et al. (2008) conducted a study investigating the effect of age on cycling, and as one of their parameters they looked at the blood lactate concentration. The two age groups in the study were 28 ± 3 years, and 57 ± 4 years. No significant differences in BL among these two age groups were found. Other studies have discovered that lactate is independent of cadence (Denadai, Ruas, & Figueira, 2006) and that both lactate and potassium are factors that relate to muscle fatigue (Tenan, McMurray, Blackburn, McGrath, & Leppert, 2011).

Physical conditions

A number of studies investigated the effects that different physical conditions have on cycling. The areas that I will review for the purposes of this study include gender and age.

A study by (Deschenes, Hillard, Wilson, Dubina, & Eason, 2006) investigated the gender differences in physiological properties such as heart rate, blood plasma levels, temperature and BL found no significant differences in most physiological responses

between untrained men and untrained women, including heart rate. They did observe a small difference in the recovery period for the blood lactate measures, with males recovering from blood lactate at a faster pace. Yasuda, Gaskill, and Ruby (2008) found that there were no gender differences in pedaling economy and efficiency in subjects with similar VO_2 max levels and ventilatory threshold levels. Similar results were observed by Billaut, Giacomoni, and Falgairette (2003). They investigated gender differences in both arm crank as well as leg crank pedaling and no differences between genders were found in either gross efficiency or delta efficiency in subjects who had similar VO_2 max levels. Another study conducted by Scott, Shaw, and Leonard (2008) also concluded that peak oxygen uptake was not different between men and women. Performance levels and time to fatigue were found to be lower in female than in male subjects. Female subjects also reached their peak power level slower than male subjects but there was no difference found in terms of time to recovery (Billaut et al., 2003). In terms of efficiency in cycling, some studies have concluded that the main difference between genders may be attributed to body composition, specifically lean leg mass (J. Hopker, Jobson, Carter, & Passfield, 2010; Latin, Berg, Tolle, Tharp, & Lahmann, 1997; Neder, Nery, Andreoni, Sachs, & Whipp, 2000).

As might be expected, some factors of exercise are influenced by age. Research has determined that the effects of cadence on cycling performance differs between young and old cyclists. Older cyclists prefer to pedal at lower cadence than younger subjects, and that it is actually more disadvantageous for older cyclists to use high cadences (Sacchetti, Lenti, Di Palumbo, & De Vito, 2010). Older age was also associated with a decrease in exercise efficiency and an increase in the oxygen cost of exercise, which contributes to a

decrease in exercise capacity (Woo, Derleth, Stratton, & Levy, 2006). However, a study conducted by Wyatt and McCarthy (2003) found that ventilatory capacity was not a major contributor to the decrease in exercise tolerance due to aging. Proctor et al. (1998) determined that neither age nor gender had a significant impact on oxygen consumption (which is directly associated with metabolic efficiency) during submaximal cycling among endurance-trained individuals. This would support the claim made by Woo et al. (2006) that age-related changes are reversed with exercise training, which improves efficiency to a greater degree in the elderly than in the young. Balmer et al. (2008) compared cyclists in two different age groups, seniors (28±3 years) and veterans (57±4 years), in two different conditions: a graded aerobic test, and a 16.1 km time trial. They discovered that overall performance declines with age. The senior group had higher peak values for power output, heart rate, cadence, oxygen uptake and ventilation than the veteran group. Despite the higher levels observed among the younger cyclists, Balmer et al. (2008) found that peak BL, respiratory exchange rate levels, and economy were similar between age groups. This suggests that *relative* economy and efficiency in cycling does not vary according to age, but absolute values observed may differ. Ciolac, Brech, and Greve (2010) found that healthy older women are able to perform with the same increasing exercise intensity as younger women suggesting that there is not a significant difference between older and younger subjects in terms of their ability to participate in progressively intensive exercises.

An additional area of research where age related differences were found is in terms of biomechanical properties. A study conducted between children and adults at a cadence of 90 rpm could be related to different anthropometric characteristics (R. Martin, Hautier,

& Bedu, 2002). It would follow that as all subjects are adults, anthropometrical values should not play as much of a role in contributing to biomechanical differences resulting from age.

Backward pedaling

One aspect of pedaling technique that has not received much attention in research is the direction of pedaling.

Thorstensson (1986) investigated the mechanics of backward walking. Forward and backward walking mirrored each other in terms of the movement trajectories, the angular displacements of the hip, knee and ankle showed a similar pattern and magnitude. However, the muscles did have a different reaction. The flexors and extensors of both the feet and the hip switched their function in backward walking in order to produce the backward movement of the leg. The knee extensors shifted their activation phase and prolonged the duration of their activation. The muscle recruitment in backward walking was quite different from that of forward walking. Backward walking has also been found to produce a greater ROM in extension of the knee, thus reducing patellofemoral joint loads (Neptune & Kautz, 2000). In the past, backward walking has been used as rehabilitation for a number of knee injuries.

Cycling is also commonly used as a rehabilitation strategy for patients suffering from knee injuries. Backward pedaling has also recently been investigated as an alternative to forward pedaling for rehabilitation based on discoveries made with respect to backward walking (Neptune & Kautz, 2000). Neptune & Kautz (2000) found that pedaling in the backward direction reduced the load placed on the tibofemoral joint, but

increased the load placed on the patellofemoral joint. Based on these results, it would depend on what type of knee injury the patient experienced as to whether or not backward pedaling would be recommended in rehabilitation. A study conducted by Bressel (2001) came to a similar conclusion, that pedaling backwards actually placed greater force on the patellofemoral joint (110%). He explained that this greater force on the joint resulted from a greater force on the quadriceps muscle (149%) when pedaling in the backward direction than pedaling in the forward direction. He concluded that there was not sufficient data to conclude that backward pedaling is a good alternative to forward pedaling in knee rehabilitation efforts.

Spinnetti (1987) investigated the power that can be generated from pedaling backward as opposed to forward. He discovered that a person is able to generate more power pedaling backward than forward. He suggested that this increase in power resulted from an increased torque in the backward pedal pattern. He suggested that more muscle groups are recruited when pedaling backward. A number of researchers have observed that, unlike backward walking, backward pedaling exhibits a phase shift (180°) of only the muscles contributing to the anterior/posterior motion of the pedaling; all other muscle seemed to contribute the same in the backward direction as they did in the forward direction (Neptune & Kautz, 2000; Raasch, 1997; C. Raasch & Zajaz, 1999; Ting et al., 1999). A muscle phase shift was observed in the biceps femoris (BF) and semimembranosus (SM), responsible for posterior motion, as well as the rectus femoris (RF), contributing to anterior motion. Phasing in vastus medialis (VM), tibialis anterior (TA), gastrocnemius medialis (GM), and soleus (SOL) were unaffected by pedaling direction, with VM and SOL contributing to extension, GM to plantar flexion, and TA to

dorsi flexion. C. Raasch and Zajaz (1999) explained that the phase shift of the anterior/posterior muscles occurred as a result of different limb kinematics, and concluded that, despite the phase shift, the muscles still performed the same function.

Experimental design

Measurement of Sub-maximal power output

Sub-maximal (sub-max) power output refers to a power output that can be sustained for a given amount of time, in order to ensure the use of the cardiovascular system. Several studies have used differing protocols in order to determine the sub-maximal power output. The general idea is that the test begins at a low level of resistance, which is maintained for a specified period of time after which the resistance level is increased in stages that must also be maintained for that same period of time. The magnitude of the increments vary from protocol to protocol, as does the duration of each stage. Some testing procedures increase the resistance level in one-minute stages (Argentin et al., 2006; Rodrigo R. Bini et al., 2008; Elske, Hawley, Hopkins, Mujika, & Noakes, 1998; Knight-Maloney, Robergs, Gibson, & Ghiascand, 2002; Malek, Coburn, & Tedjasaputra, 2009; Wallman, Morton, Goodman, & Grove, 2004), others used two or three minute stages (Argentin et al., 2006; Chen, Fan, & Peng, 1985; Denadai et al., 2006; Leirdal & Ettema, 2009; Lorås, Ettema, & Leirdal, 2009; Marcora & Staiano, 2010; McGhie & Ettema, 2011; Wyatt & McCarthy, 2003). The resistance level at which the testing started also varied from protocol to protocol. Some protocols began with no resistance (Hodges, Sporer, Lane, & McKenzie, 2010; McGhie & Ettema, 2011), while others started at a resistance level of 50W (Bailey, Hall, Folger, & Miller, 2008; Rodrigo R. Bini et al., 2008; Knight-Maloney et al., 2002; Marcora & Staiano, 2010; Wyatt &

McCarthy, 2003), 100W (Bieuzen, Lepers, Vercruyssen, Hausswirth, & Brisswalter, 2007; Elske et al., 1998; Leirdal & Ettema, 2009; Lorås et al., 2009; Sanderson & Black, 2003) and even 150W (Bentley, McNaughton, Thompson, Vleck, & Batterham, 2001). The amount that the resistance level was increased at each stage of the test also varied from protocol to protocol, with increments ranging from 12W to 50W (Bailey et al., 2008; Chen et al., 1985; Leirdal & Ettema, 2009; Lorås et al., 2009; Marcora & Staiano, 2010; Wallman et al., 2004). The most common increment cited was 25W (Argentin et al., 2006; Rodrigo R. Bini et al., 2008; McGhie & Ettema, 2011; Sanderson & Black, 2003; Savelberg et al., 2003; Wallman et al., 2004). Due to equipment limitations, I am only able to increase resistance levels in 10W increments, so I chose to increase the resistance by 30W at each stage. This increment has been used in previous studies as well (Bentley et al., 2001; Bieuzen, Lepers, et al., 2007; Hodges et al., 2010; Knight-Maloney et al., 2002).

Recover period

Costa, De Matos, Pertence, Martins, and De Lima (2011) conducted a study where they tried to reproduce a test to exhaustion on the same test day. The two tests produced similar results in all parameters measured, including heart rate, blood lactate, and oxygen uptake, with the exception of one parameter: time. The second test conducted had a shorter time to exhaustion than the first, but physiological factors stayed the same for both tests. There is evidence that the internal body clock plays a role in sport performance, especially when “maximal or sustained muscle work is required,” (Reilly & Waterhouse, 2009) and it has been suggested that the time of day influences performance (Elske et al., 1998; Reilly & Waterhouse, 2009).

3-D motion capture

3-D motion capture enables researchers to obtain kinematic information in three different planes: sagittal, horizontal and frontal planes. It is advantageous to be able to obtain this data in the three planes in order to get a more accurate picture of changes in joint mechanics during dynamic movement. Sayers and Tweddle (2012) used 3D motion capture to analyze the changes that occur in the thorax and pelvis in a high intensity ride. Shan (2008) investigated a bicycle saver product. He used 3D motion capture to analyse differences in joint angles (specifically of the hip, knee and ankle) as trials progress, giving some insight to motor control. 3-D motion capture may be used to give us some feedback regarding the correlation of muscle fatigue with loss of motor control.

Pedal forces

Among all of the studies that have investigated the complex relationship between cadence, power and efficiency, few studies have actually analysed the three dimensional forces exerted on the pedals throughout a pedal revolution. One group of researchers (Sanderson & Black, 2003) conducted a study analyzing the efficiency of force on the pedal as the subject cycles, comparing the force distribution and the angles and moments of the hip, knee and ankle at the beginning of an endurance ride to exhaustion to those same measurements taken at the end. They found that pedal force efficiency improved toward the end of the test. However, they observed that the recovery phase was less effective at the end of the session and more force was required throughout the remainder of the pedal revolution. This would presumably cause the cyclist to reach exhaustion faster. They suggested that training the pattern of force application might be helpful in enhancing a cyclist's endurance. Using data collected from force pedals, Sanderson and

Black (2003) also found that as the resistance level increases, there is more time spent pulling than pushing, and that the push/pull force occurs at different angles of rotation at different intensities. Korff, Romer, Mayhew, and Martin (2007) also investigated the effect of the pull on the upstroke of the pedal pattern and discovered that mechanical effectiveness was greater and gross efficiency was lower when subjects implemented a pull. He concluded that mechanical effectiveness is not indicative of gross efficiency across pedaling techniques. The magnitude and direction of the pedal forces has been found to be dependent on the intersegmental orientation of seat tube, crank position, upper and lower leg, and foot. (de Groot et al., 1994).

Summary and rationale of the study

In this project I am investigating a new bicycle design that allows a rider to pedal either forward or backward to create forward propulsion. The goal of this study is to determine if the ability to pedal in both the forward and the backward direction increases efficiency. In order to investigate the possibility of a muscle memory or training effect, I chose to compare trained cyclists and untrained cyclists. Subjects for this study consisted of adults aged 18-65 years. Anthropometric differences of young subjects compared with adults causes differences in biomechanics (R. Martin et al., 2002). From the literature we learn that adults younger than 70 do not respond significantly differently in terms of the physiological parameters (heart rate and blood lactate) that I chose to observe. We also learn, that there do not seem to be any significantly different gender-related physiological responses for these parameters. Thus, I chose to include both males and females in this study.

This thesis examines biomechanical and physiological properties in order to gain insight regarding the fatigue process as well as provide an understanding of the effects of fatigue on muscle control. Biomechanical properties investigated include the force exerted on the pedal and the angles of the joints of the lower limbs. As part of the pedal force investigation I observed the magnitude of the force exerted as well as the dispersion of those forces. Several physiological parameters are used to provide some insight to and understanding of the fatigue process and to monitor the exercise intensity. These parameters include EMG, heart rate and BL. I also monitored the time to fatigue. The combination of all of these parameters should enhance understanding of the process of fatigue and the effects from pedaling in the bi-directional pedal pattern on fatigue.

Chapter 3: Methodology

In order to evaluate the efficiency of the bi-directional bicycle, the investigation included a pre-test study looking at the efficiency of backward pedaling compared to forward pedaling, as well as the efficiency of the bi-directional bicycle compared to a fixed-gear bicycle. Protocols and test procedures used in this thesis project were approved by the Human Subject Research Committee at the University of Lethbridge.

Standardization of test conditions – protocol set-up

Prior to the beginning of this project, a preliminary study was performed with a small group. The purpose of this preliminary study was two-fold: to determine the ratio of sub-maximal power output when pedaling forward to the sub-maximal power output when pedaling backward, and to evaluate the efficiency of the new bicycle design compared to a fixed-gear bicycle. This preliminary study was necessary to establish baseline data to work from, as no previous research provided a test protocol that might be applicable in the current study.

Methodology

Eight subjects (five male, three female; ages ranged from 23-63) completed four different sub-maximal power tests on four different sessions, with a minimum of 24 hours of rest between sessions. Tests were conducted on two different bicycles: a fixed gear road bicycle and a prototype of the new bicycle design invented by Dr. Gongbing Shan from the University of Lethbridge and built in conjunction with Southern Alberta Institute of Technology. Each subject completed a sub-maximal power test on both the fixed-gear bicycle and the prototype, in two different pedal patterns (forward and

backward) on each bicycle. Tests were conducted at the same time of day on different days for each subject.

Before commencing with the sub-maximal sustained power output test, subjects began each test day with a maximum five-minute warm-up on a stationary trainer with little or no resistance. Patterned after a similar test conducted by Long and Thomas (1993), each sub-maximal power output test began at a resistance level which produced a power output (PO) of 50W and increased by 30W every three minutes. Subjects were instructed to remain seated throughout the test (Elske et al., 1998), and pedal within the set range of cadence (70-110 rpm) until they reached a state of exhaustion. Exhaustion was determined to occur either when subjects were no longer able to maintain a cadence of 70 rpm (Rodrigo R. Bini et al., 2008) or when the subject determined that they were exhausted and could not continue with the test. Vigorous verbal encouragement was provided to each subject throughout all tests in order to facilitate their best performance.

The order of the pedaling patterns (forward or backward) were randomly assigned to each subject. Since, the two bicycles had different wheel sizes, hooking up the bicycles on the trainer required some adjustments. As a result, I did all of the testing on the fixed gear bicycle first, then on the bi-directional bicycle in order to eliminate the possibility of altered resistance levels resulting from a different set-up and to maintain consistency with the trainer.

Data was recorded and then analyzed using Excel. On the fixed gear bicycle I found that the sub-maximal sustained PO in the backward direction was approximately 83.3% ($\pm 9.5\%$) of that in the forward direction for each individual, with only one exception. On

the bi-directional bicycle, I found that the sub-max PO in the backward direction was approximately 87% ($\pm 5.8\%$) of that in the forward direction.

Results from this preliminary study showed that, in general, pedaling in the backward direction is less efficient than pedaling in the forward direction in terms of the maximum sustained power output. This preliminary study also showed the relative efficiency of the bi-directional bicycle to be similar to that of the fixed gear bicycle when comparing the forward direction to the backward direction. The ratio of forward to backward maximum sustained power output between the two bicycles was the same. However, it should be noted that the maximum sub-maximal power output attained on the fixed gear bicycle was higher in both directions than it was on the bi-directional bicycle for all subjects involved in the preliminary study. This may result from the difference in design of the two bicycles, the fixed-gear bicycle being more efficient because of the simplistic design of the pedal mechanism.

Subject recruitment and screening

Subjects were recruited through the Headwinds Cycling club in Lethbridge, Alberta, Canada, as well as through the University of Lethbridge. A notice requesting volunteers for participation in the study was posted on the Headwinds Cycling club website, and four kinesiology classes were visited on the University of Lethbridge campus to recruit subjects for this study. All subjects were volunteers and were not rewarded for their contributions. Each subject signed two consent forms (see Appendix A) informing them of the purpose of the study, and the procedures that would be followed. One form outlined the study from a biomechanical perspective, while the second form outlined the physiological aspects of the study.

Prior to participating in this study, subjects' health and ability to participate were screened using the PAR-Q question form, which is designed to identify people who may experience health risks when participating in physical activity. All subjects who participated in this study passed the PAR-Q with no major health concerns identified.

Due to limitations in the amount I could adjust the bicycle to fit the subjects, I also had to screen the subjects based on body measurements. The main limiting factor was the height of participants. I was able to make minor adjustments to the bicycle in order to fit it properly to all participating subjects. These adjustments included seat height, seat tilt, stem length, and handlebar placement. Frame size could not be adjusted, nor could the length of the crank arms. These limitations resulted in the disqualification of three volunteers from the subject pool.

Thirty-three Caucasian subjects started the study, but due to unexpected injuries two subjects had to withdraw, and one subject failed to complete all four sessions due to scheduling conflicts. Subjects were categorized into two groups; trained cyclists, including tri-athletes (thirteen males, five females, age 31.4 ± 11.1 years, body weight 77.2 ± 12.3 kg, body height 177.7 ± 5.4 cm, 9.6 ± 9.7 average years of training) and untrained individuals (eight males, seven females, age 28.6 ± 11.3 years, body weight 67.1 ± 11.0 kg, body height 176.4 ± 7.9 cm). Trained cyclists were defined as people who had a minimum of two years cycling experience, and were training a minimum of five hours per week at the time of data collection. Untrained individuals were defined as those who did not train for any specific sport regularly, but may have been physically active in their lives.

Equipment specifications

For this study, a Cervelo bicycle (2007) frame (size 56 inches) was used, with top tube length measuring 20 inches. The seat height and stem length were adjusted in order to fit the bicycle to each subject individually. Each subject used the same bicycle set-up for all four of their individual trials.

The new bicycle design under investigation contained a modification to the crank-pedal system accommodate the forward/backward pedal system (see Figure 2 below). The modification allowed a cyclist to pedal either forward or backward in order to propel the bicycle in the forward direction. This mechanism was built at the Southern Alberta Institute of Technology and was completed at the end of 2008.



Figure 2 – Modification of bidirectional crank system. Also included in photo is a picture of the force pedal.

The bicycle was mounted on a Tacx CE T1680 Flow Ergotrainer (2007) in the lab. A special pedal (Kistler Force pedal constructed using the Kistler 3 component force sensor model 9251A, 2008) was used to measure the forces exerted in three separate dimensions: vertical, medial/lateral and anterior/posterior.

Five channels of an eight-channel wireless NORAXON (NORAXON U.S.A., Inc., Arizona, U.S.A.) EMG system, capturing at a rate of 1000Hz, was used to monitor muscle activation levels.

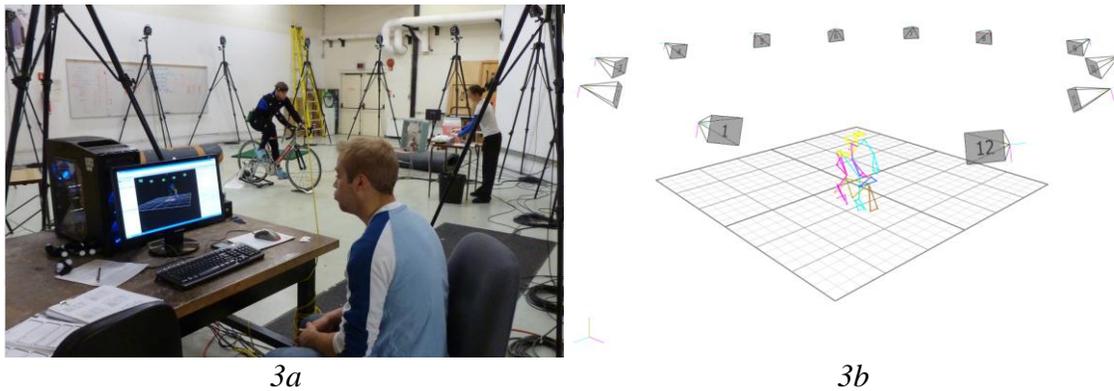
A twelve-camera VICON 3D motion capture system (Oxford Metrics Ltd., Oxford, England) was used to quantitatively determine the measurements of and record the movements of subjects as they were cycling. VICON software (Life Sciences Software Package, 2010) was configured to capture movement at a rate of 200 frames per second and reconstruct the captured movements in 3D computer space. Calibration residuals were found following VICON's guidelines and were accurate within 1 mm.

Blood lactate was measured at two minute intervals during each session. A drop of blood was drawn from the subjects every two minutes using Multilet supersoft needles and Lactate Pro blood lactate test strips. BL were measured using the Arkray Lactate Pro blood lactate test meter. Heart rate was monitored using a wireless POLAR heart rate monitor, model FS2c.

Experimental procedures and data collection

Lab set-up

The lab was set up with the bicycle under investigation centered in the middle of the room surrounded by 12 VICON infrared cameras positioned in a circle around the subject (see Figure 3a and 3b below).



Figures 3a and 3b – Picture (3a) and computer re-construction (3b) of lab set-up.

Throughout each trial, a fan was positioned to face the subjects at an angle to help regulate their body temperature while cycling and to avoid overheating (Elske et al., 1998). To avoid dehydration as they cycled, subjects were provided with a choice of either water or an electrolyte solution to drink as they desired.

Subject set-up

For each test day, subjects were instructed to wear comfortable shorts, a t-shirt, and running shoes. Subjects were outfitted with wireless electromyography (EMG). Five channels of the eight-channel wireless EMG system were used. Surface electrodes were placed on the following muscles of the right leg of each subject: Biceps Femoris (BF),

Tibialis Anterior (TA), Vastus Medialis (VM), Vastus Lateralis (VL), and Gastrocnemius Medialis (GM).



Figure 4 – Subject with wireless EMG

Subjects were then dressed in a stretchable black garment with full-body coverage. A set of 39 reflective markers were attached to the suit to indicate anatomical landmarks (see Figure 5a and 5b below). Four markers were placed on the head; the left and right temples, and the left and right posterior portion of the parietal bone. The markers on the head were positioned so as to be parallel to the ground when the subject was facing straight ahead. Markers placed on the upper body included the C7, T10, right back, sternal notch, xiphoid process as well as the acromion processes, upper arm (arbitrary placement), lateral epicondyles of the humerus, lower arm (arbitrary placement), styloid processes of both the ulna and the radius, and the third metacarpophalangeal joint on both the left and right sides of the body. The markers on the lower body were also placed on both the right and left sides, and included the following locations: the anterior superior

iliac crest, posterior superior iliac crest, upper leg (arbitrary placement), lateral condyles of the tibia, lower leg (arbitrary placement), lateral malleolus of the fibula, calcaneal tuberosity and the head of the hallucis. Four markers were assymmetrically placed on both the upper and lower arms and legs to differentiate the left and right sides of the subject and facilitate computer econstruction of data. Markers reflected infrared light signals that were detected by the motion capture VICON cameras situated around the subject.



5a



5b

Figure 5a and 5b – Photo of subject with suit and markers placed on anatomic positions of the body, and mounted on the bicycle; front view (5a) and back view (5b)

Testing procedures

Each subject participated in four separate days of data collection. The duration of each ride was to voluntary fatigue. This is defined as the point at which subjects felt they

were no longer able to continue pedaling at the set resistance level, or their pedal cadence fell below 70 rpm. Subjects had a minimum of 48 hours rest between data collection days to allow for muscle recovery, and subjects were asked to refrain from heavy exercise the day before each test so that the muscles were rested. All four days of data collection for each subject occurred at the same time of day (Elske et al., 1998; Reilly & Waterhouse, 2009).

The first day of data collection started with a base-line sub-maximal graded power output test with subjects pedaling in the forward direction on the bi-directional bicycle. Prior to cycling on the first day, the bicycle was fitted to the individual rider adjusting the seat position, stem length, and handlebar position. The same individualized bicycle set-up was used for all four test days. Subjects were then asked to perform a five-minute warm-up prior to the beginning of the test. In the graded power output test, subjects started pedaling at a 50 Watt power output (PO). Subjects were asked to maintain an RPM of 70-110 through the duration of the tests. The PO was increased by 30 Watts at three-minute intervals until the participant was no longer able to maintain the set PO level, or the minimum cadence. The PO from the last completed level was recorded as their maximum sustained PO (SPO). This initial data was used to determine the resistance level for each individual in subsequent lab sessions.

Days two, three and four in the lab consisted of three different pedaling configurations: forward pedaling only (FO), backward pedaling only (BO) and bi-directional pedaling (BI) which consisted of pedaling forward for seven minutes, then backward for three minutes for the duration of the test. The order of these three conditions was randomly assigned for each subject. Hodges et al. (2010) concluded that

one session would not benefit, nor hinder performance, so I was not concerned that a previous session would alter the data collection for subsequent sessions, but the order of conditions was randomized in order to meet scientific protocol.

To the best of my knowledge, there is no quantitative research related to a combination of forward and backward pedaling. Since the focus of the study was to test the efficiency of the new bicycle design, specifically examining the effect of a bi-directional pattern a ratio of forward to backward pedaling was required. I used an empirical method to determine a usable ratio for this study. Since backward pedaling is an unfamiliar motion, it is not as fluid of a movement and is not as efficient as forward pedaling, as was verified in the preliminary study. Because of this, less time was allotted to pedaling backward than forward for the bi-directional pedal pattern. However, sufficient time pedaling backwards is required to find a rhythm before switching to forward pedaling. Prior to the beginning of testing, a number of single trials were conducted to determine the ratio of seven minutes forward to three minutes backward pedaling when testing the BI pedal pattern. Since it was not my intention to find an optimal ratio, and some practice pedaling in the backward direction could change the feel of the pedaling, future studies may explore what an optimum ratio of forward to backward pedaling might be.

After obtaining the subjects' peak forward pedaling sustained power output (SPO), resistance level for forward pedaling were set to 90% of this value. This value is based on studies conducted by Rodrigo R. Bini et al. (2008) and Hansen et al. (2002). For backward pedaling, the resistance level was set to 87% of the forward pedaling resistance level ($SPO \times 90\% \times 87\% = 78\%$ of SPO) in order to determine the resistance level for

backward pedaling for subsequent testing days. This percentage was chosen based on results from the preliminary study. The resistance level for bi-directional (BI) pedaling was adjusted according to the direction the subject was pedaling in order to obtain comparable results in the BI pedal pattern.

On each trial day, subjects were instructed to pedal at the resistance level which would produce the desired PO and to maintain a cadence between 70-110 until voluntary fatigue. This is a method that has commonly been used in past research (Rodrigo R. Bini et al., 2008; Rodrigo R. Bini & Diefenthaler, 2010; R. R. Bini, Diefenthaler, & Mota, 2010). A subject pedaling to voluntary fatigue allows them to gauge their own effort and performance.

On test days two, three and four, as subjects cycled at the appropriate resistance level, ten seconds of data was collected every two minutes using the 12 camera VICON motion capture system. These captures provided three-dimensional coordinate positions of all markers. Each subject was allowed a five-minute warm-up (pedaling in the pattern that they would be pedaling on that particular day of testing) prior to the start of testing. Each testing condition started with a ten-second data collection to be used as a baseline. Then, ten-second captures were made every two minutes thereafter until subjects reached voluntary fatigue, or were unable to maintain a minimum cadence of 70 rpm, at which time one final ten second data collection was taken (even if it had not yet been two minutes since the last data collection). BL and heart rate were measured for each subject. I tested the subjects' resting blood lactate level to provide a baseline for comparison. Throughout the duration of each trial, BL and heart rate were measured and recorded in two minute intervals, each immediately following the ten second data collection period,

and a final blood lactate level and heart rate was recorded as soon as the subject stopped pedaling.

Data analysis

Post-data processing

Data was processed using VICON software (Life Sciences Software Package, version 2010). The raw data that was collected using the VICON camera system was filtered using a five-point smoothing filter (1-3-4-3-1 function). A full-body biomechanical model of each subject consisting of 15 segments was constructed. These segments include the head and neck, upper trunk, lower trunk, and right and left segments of each of the following: upper arm, lower arm, hand, upper leg (thigh), lower leg (shank), and feet. From the coordinate data collected I was able to determine not only the position of each segment and joint, but also the angles of each joint at any given period in time. The joint coordinate data was exported using Bodybuilder (Life Sciences Software Package, version 2005) into ASCII (csv) format. Microsoft Excel (version 2010) was used to read and analyze this data. EMG data was processed and filtered using the Origin program (version 3.0). Using this program, I was able to calculate the median power frequency for each muscle from the 10-second data collections. This data was used to compare muscle activation levels as each trial progressed and to see if there were any changes in the patterns of activation of selected muscles. No post-data processing was required for the blood lactate, heart rate, or duration of cycling time measures.

In analyzing this data, a MATLAB program (version R2011b) was designed to extract data points that were of interest. Parameters that were exported using MATLAB

included the crank arm angle where the maximum pedal force in the vertical direction was recorded on each pedal rotation (looking at both the push force as well as the pull force) and the angles of several joints (including the hip in terms of flexion/extension as well as medial/lateral positioning, the knee in flexion/extension only, and ankle in terms of both flexion/extension and medial/lateral positioning at those same locations). The time difference between the maximum push force on the pedal and the maximum net force (the maximum of the averages of the forces in the vertical, anterior/posterior and medial/lateral directions) that occurred for each rotation of the pedal was also investigated. I also looked at the angle of the crank where the maximum muscle contraction happened for each of the five muscles that were monitored (GM, BF, VM, VL, TA). Further, I recorded the joint angle where the maximum push and pull forces occurred for each revolution of the pedal.

The MATLAB program used for this can be made available upon request.

Statistical analysis

Data was analyzed using both descriptive and analytical statistics. A combination of ANOVA and t-tests were done to determine significance.

Chapter 4 – Results

Kinetics

Kinetic measures in this study include data obtained from the force pedals. This data can be categorized into two areas: magnitude of force on the pedals and the distribution of the maximum force in the pedal stroke.

Force magnitude

The maximum pedaling force is expressed as a percentage of the subjects body weight (relative comparison) in order to normalise the results. The average amount of force expressed as a percentage of body weight did not change significantly ($p>0.05$) from the beginning to the end of the trial for the trained group in either the push or pull forces, both decreasing by 15.88% and 22.45% respectively (see Figure 6).

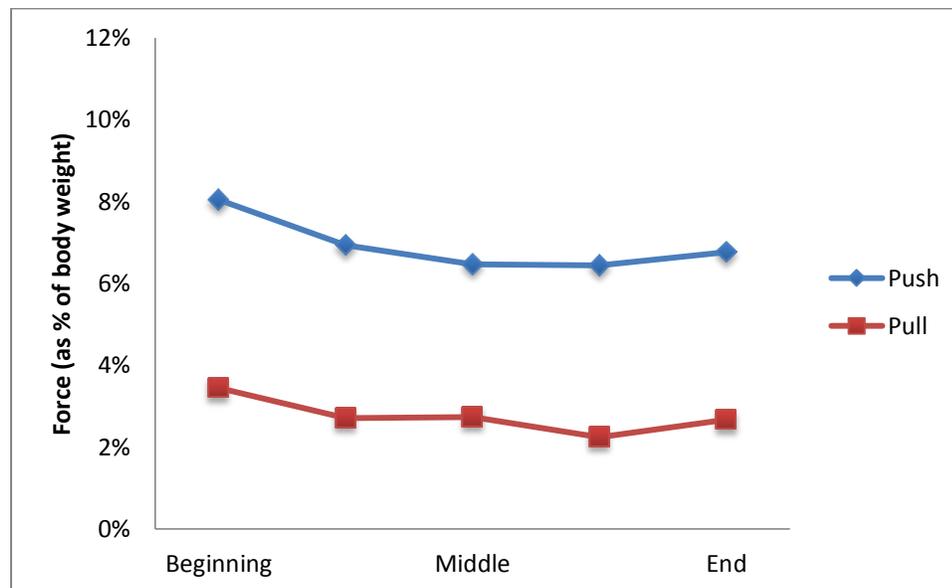


Figure 6 - Comparison of pedal force expressed as a percentage of body weight for both push force and pull force in trained subjects in the FO pedal pattern;

FO: Forward only.

However for the untrained group both the push and the pull forces actually increased from the beginning to the end of the trial by 46.44% and 43.69% respectively (see Figure 7). The increase of the push force was significant ($p \leq 0.05$) while the increase of the pull force was highly significant ($p \leq 0.01$).

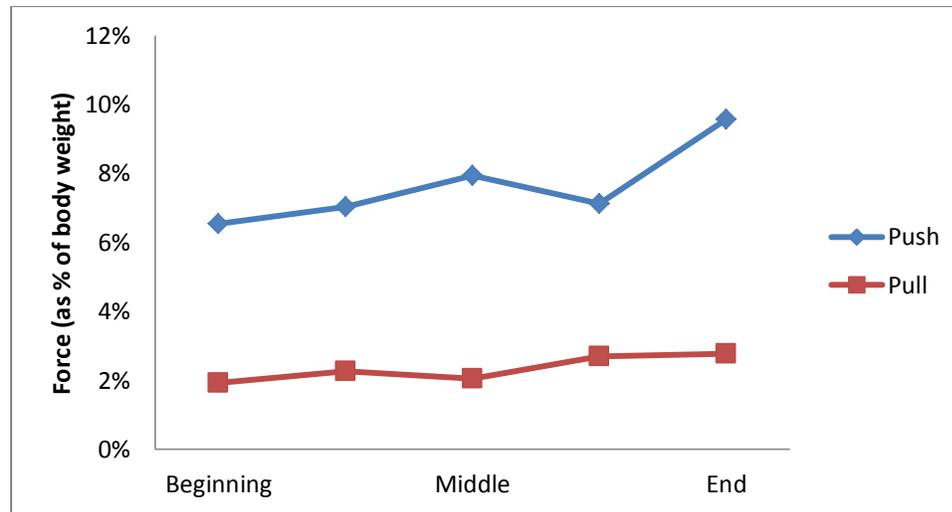


Figure 7 - Comparison of pedal force expressed as a percentage of body weight for both push force and pull force in untrained subjects in the FO pedal pattern;

FO: Forward only.

In terms of the magnitude of the push and pull forces, results for trained and untrained subjects were similar in the BO and FO pedal patterns. The push force for the BO pedal pattern increased by 11.47% and the pull force increased by 12.87% by the end of the trial as compared with the beginning of the trial for trained subjects (see Figure8). The changes were not significant ($p > 0.05$).

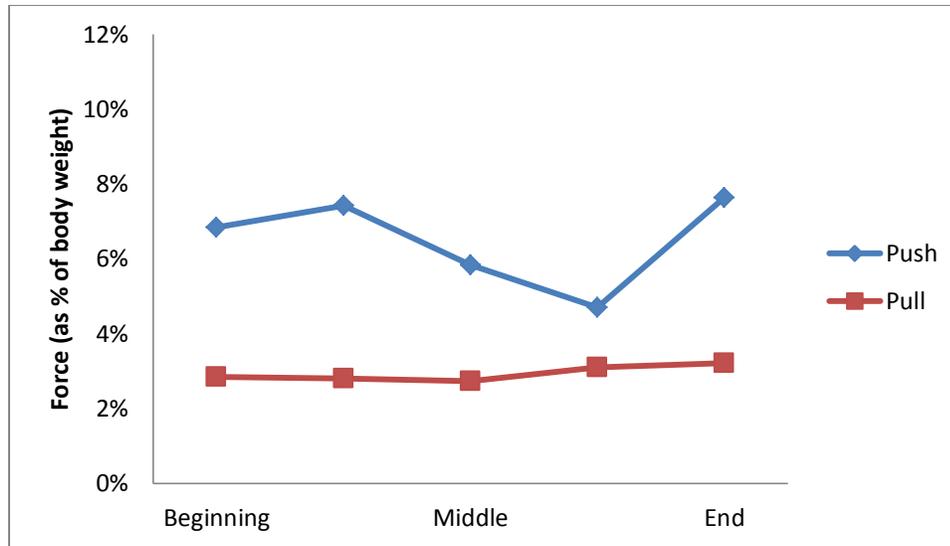


Figure 8 - Comparison of pedal force expressed as a percentage of body weight for both push force and pull force in trained subjects in the BO pedal pattern;

BO: Backward only.

Untrained subjects had a larger change. The push force increased by 26.73% and the pull force decreased by 15.81% by the end of the trial (see Figure 9). The change in the push force was highly significant ($p \leq 0.01$), while the change in the pull direction was not significant ($p > 0.05$).

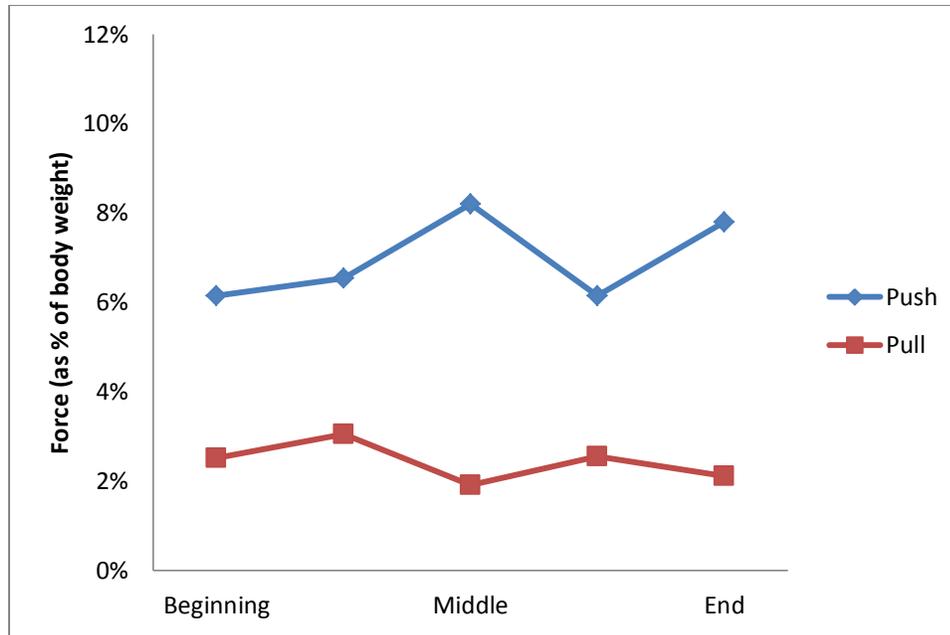


Figure 9 - Comparison of pedal force expressed as a percentage of body weight for both push force and pull force in untrained subjects in the BO pedal pattern

BO: Backward only.

Highly significant differences ($p \leq 0.01$) were observed between the magnitude of the push and pull forces for all measurements in all pedal patterns for all subjects (see Figures 6-9 above).

Force distribution

The force pedal data showed a consistent pedal pattern clearly indicating the location of both the maximum push force as well as the maximum pull force in each revolution of the pedal crank during the capture. In the first data collection of the trial the location of the push forces are consistently in the same locations, while the pull forces have slightly greater distribution. In the last data collection of the trial the location of the push and pull force varies. In Figure 10 we see that at the beginning of trials (quadrant 1) the distribution of the maximum forces on the push are clumped in a very similar place,

where the end of trial (quadrant 2) we can see that these points are more spread out. A similar pattern is observed with the pull points from the beginning to the end. It should also be noted that the distribution of the push force and the pull force differ as well; the pull force has a greater variance than does the push force in both the beginning (quadrant 1) and the end of the trial (quadrant 2) This observation was consistent among both trained and untrained subjects. You can also see that both of these patterns were consistent when pedaling in the backward direction (see quadrants 3 and 4). When looking at the pattern between the forward pedal pattern and the backward pedal pattern, it should be noted that the forces in the backward pedal pattern have a much larger distribution at both the beginning and at the end of the trial than the forward pedal pattern (see quad 1 vs. 3 and 2 vs. 4).

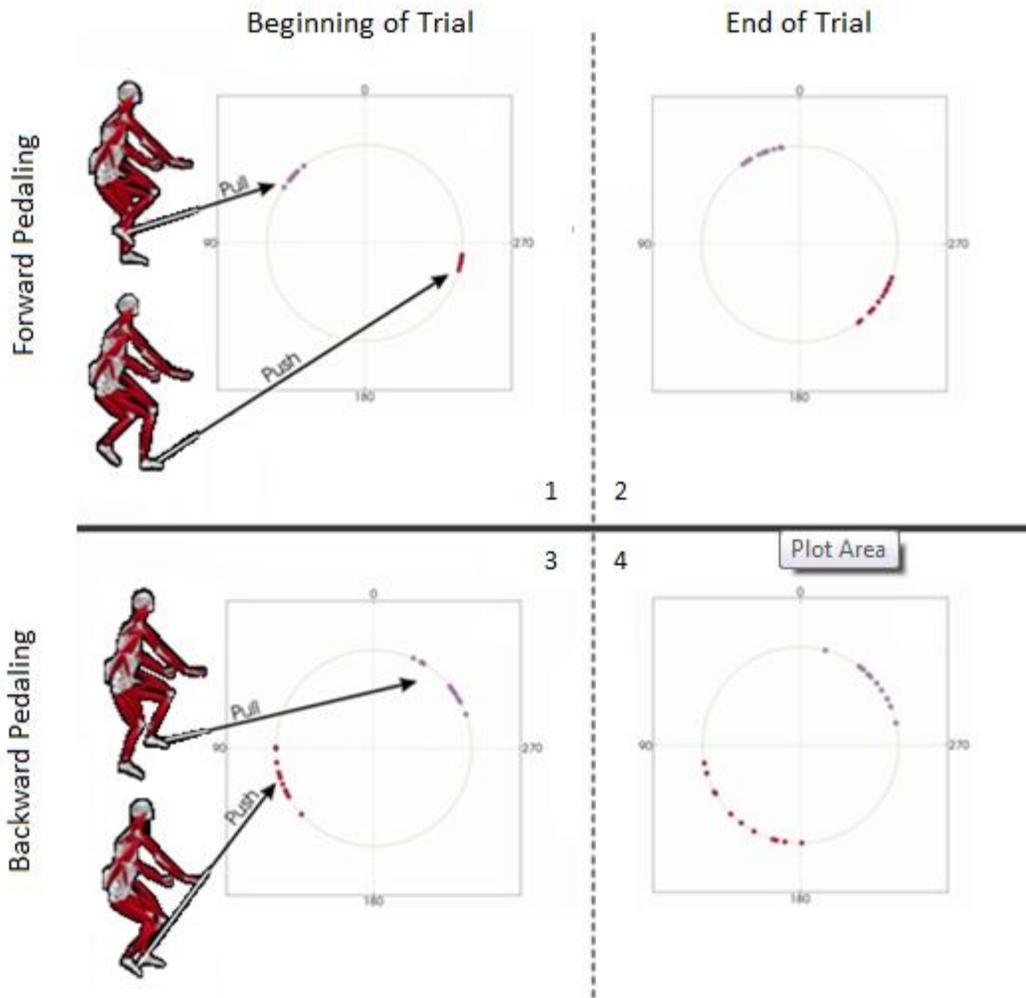


Figure 10 - Location of the maximum push force and pull force for each revolution in a 10-second measurement at the beginning of the trial compared to the end of a trial for both the FO and BO pedal patterns;
 FO: Forward only; BO: Backward only.

Trained subjects showed a 66.51% increase in range of position (ROP) of the crank at the point where the maximum push force occurred from the beginning to the end of the trial in the FO pedal pattern, with a standard deviation increasing by 185.73% ($16.31 \pm 7.45^\circ$ at the beginning compared with $27.15 \pm 21.30^\circ$) (see Figure 11). The push

force saw a gradual increase in ROM. At the beginning, the range in the angle of the crank was $16.31 \pm 7.45^\circ$, $20.31 \pm 21.43^\circ$ after the first quarter, $24.69 \pm 21.79^\circ$ at the half-way point, $26.77 \pm 24.87^\circ$ after the third quarter, and a range of $27.15 \pm 21.30^\circ$ at the end of the trial. The increase of the range of the angle for the push force from the beginning to the end of the trial was significant ($p \leq 0.05$).

For trained subjects, the range of the crank angle for the maximum pull force showed a different pattern than that of the push. The pull force saw a decrease by 28.86% (this was not significant ($p > 0.05$)) from the beginning to the end, but an overall change of 52.53%. The standard deviation of the range of the pull force decreased by 61.83% from the beginning to the end of the trial (31.04° compared with 11.85° respectively) for the trained subjects in the FO pedal pattern (see Figure 11). At the beginning, the range in the angle of the crank was $35.25 \pm 31.04^\circ$, $24.31 \pm 16.12^\circ$ after the first quarter, $37.08 \pm 28.19^\circ$ at the half-way point, $25.46 \pm 11.86^\circ$ after the third quarter, and a range of $25.08 \pm 11.85^\circ$ at the end of the trial.

There was a significant difference ($p \leq 0.05$) between the range of the push and pull forces at the beginning of the trial for the trained subjects in the forward pedal pattern, but there were no significant differences ($p > 0.05$) between the push and pull forces throughout the remainder of the trial.

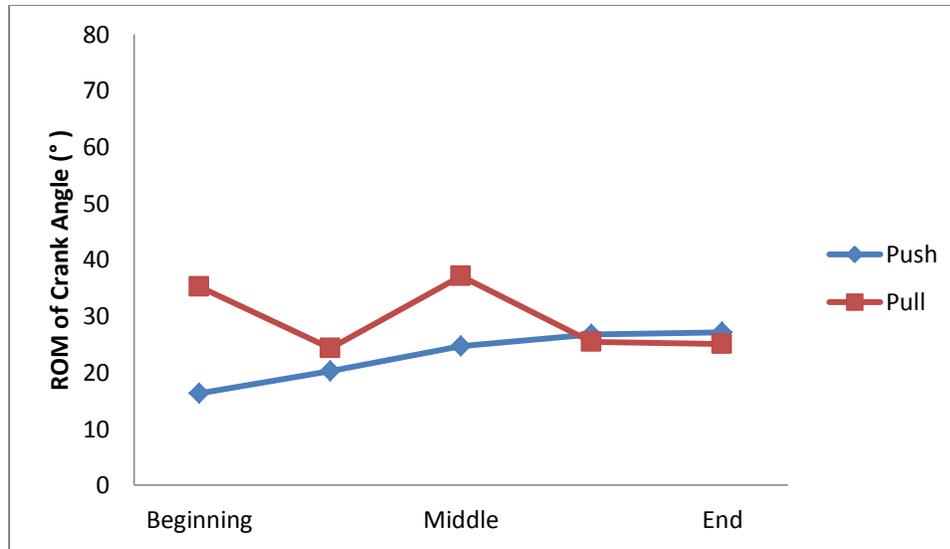


Figure 11 - Comparison of the ROP of the crank angle between push and pull forces in trained subjects for the FO pedal pattern;

ROP: Range of Position; FO: Forward only.

Trained subjects pedaling in the FO pedal pattern started with an average pull rate of 89.56%, and gradually increased to a pull rate of 98.19% at the end of the trial, an increased pull rate of 9.64%.

Untrained subjects showed an increase of 128.35% from the beginning of the trial to the end of the trial, with an increase of 150.69% in the standard deviation. This shows an even greater variation than the trained subjects in this pedal pattern. This increase was highly significant ($p \leq 0.01$). Subjects started with an average of $21.78 \pm 9.41^\circ$, then after the first quarter saw a range of $33.00 \pm 25.78^\circ$, $42.73 \pm 33.27^\circ$ and $38.33 \pm 26.95^\circ$ at the half-way point and after the third quarter respectively, and a range of $49.93 \pm 23.59^\circ$ at the end of the trial.

Untrained subjects average crank angle for the pull force in the FO pedal pattern had an increase of 36.83% from the beginning to the end of the trial, but an overall increase of 192.28% throughout the trail. The increase was not significant ($p>0.05$). At the beginning, the angle at which the greatest pull force occurred had a range of $24.00\pm 17.82^\circ$, then $27.45\pm 17.42^\circ$ and $21.53\pm 13.85^\circ$ after the first quarter and at the half-way point respectively, $24.92\pm 17.35^\circ$ after the third quarter, and $20.31\pm 7.87^\circ$ at the end of the trial. The difference between the range of the push and pull forces for untrained subjects was not significant ($p>0.05$).

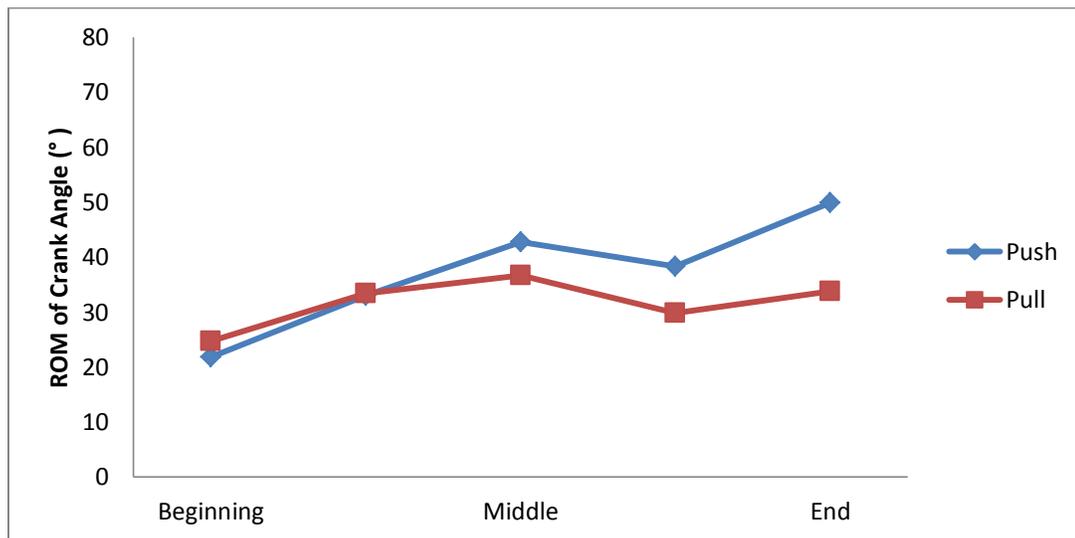


Figure 12 - Comparison of the ROP of the crank angle between push and pull forces in untrained subjects for the FO pedal pattern;

ROP: Range of Position; FO: Forward only.

Untrained subjects pedaling in the FO pedal pattern started with an average pull rate of 79.39% and ended at 93.74%, representing an increase of 18.07% throughout the trial.

There was a significant difference ($p \leq 0.05$) between the trained and the untrained subjects in the FO pedal pattern for the ROP for the push forces at the beginning and at the middle of the trial, and the difference at the end was highly significant ($p \leq 0.01$) (see Figure 13). No significant differences ($p > 0.05$) were found between trained and untrained groups in the range of the pull forces in the FO pedal pattern.

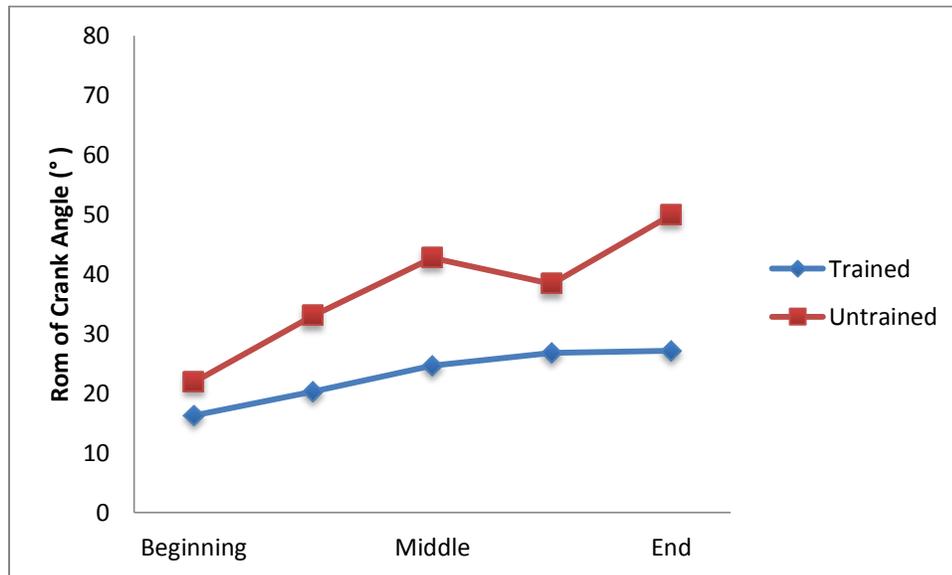


Figure 13 - Comparison of the ROP of the crank angle between trained and untrained subjects where the maximum push force occurred in the FO pedal pattern;;

ROP: Range of Position; FO: Forward only.

Trained subjects showed a decrease of 5.16% in ROP of the crank where the maximum push force in occurred in the BO pedal pattern from the beginning to the end of the trial. This change was not significant ($p > 0.05$), nor did the standard deviation vary significantly ($p > 0.05$) among data collections (6.13% decrease in SD). At the beginning, the range in the angle of the crank was $48.42 \pm 29.75^\circ$, $46.40 \pm 27.84^\circ$ after the first quarter,

41.36±35.21° at the half-way point, 36.30±21.93° after the third quarter, and a range of 45.92±27.93° at the end of the trial.

For trained subjects, the pull force in the BO pedal pattern showed an overall decrease in range by 39.44%, with a decrease of 21.92% in the SD from the beginning to the end, but an overall change of 134.80% in SD among subjects. The pull force started at a range of 50.78±21.63°, 38.70±39.66° after the first quarter, 48.20±20.96° at the half-way point, 39.80±21.69° after the third quarter, and a range of 30.75±16.89° at the end of the trial. The change in range of the pull force from the beginning to the end of the trial was highly significant ($p \leq 0.01$).

The difference between the ranges of the push and pull forces for the backward pedal pattern was not significant ($p > 0.05$).

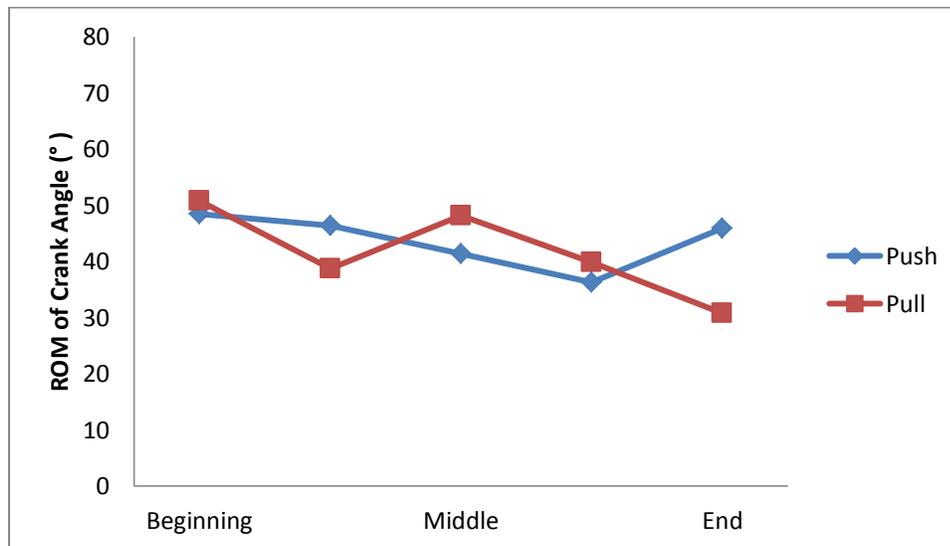


Figure 14 - Comparison of ROP of crank angle where maximum push and pull forces in the BO pedal pattern for trained subjects;

ROP: Range of Position; BO: Backward only.

Trained subjects in the BO pedal pattern increased their pull rate from 72.88% to 92.91% from the beginning to the end of the trial; a 27.47% increase.

In untrained subjects, the range of the BO push force increased by 28.40% from the beginning of the trial to the end of the trial, but an overall increase of 67.90%. Subjects started with an average of $40.50 \pm 15.04^\circ$, then after the first quarter saw a range of $68.00 \pm 21.41^\circ$, $50.17 \pm 33.79^\circ$ and $47.50 \pm 26.17^\circ$ at the half-way point and after the third quarter respectively, and a range of $52.00 \pm 31.99^\circ$ at the end of the trial.

Untrained subjects average crank angle for the pull force in the BO pedal pattern increased by 10.31% from the beginning to the end of the trial, but overall it increased 24.13% throughout the trial. At the beginning, the angle at which the greatest pull force occurred had a range of $43.10 \pm 24.57^\circ$, then $47.00 \pm 27.07^\circ$ and $46.27 \pm 32.19^\circ$ after the first quarter and at the half-way point respectively, $53.50 \pm 23.68^\circ$ after the third quarter, and $47.55 \pm 16.26^\circ$ at the end of the trial.

Neither of the changes in range for the push or the pull forces were significant ($p > 0.05$) for the untrained subjects in the backward pedal pattern. Nor were there any significant ($p > 0.05$) differences between the ROP of the maximum push or the maximum pull forces throughout the duration of the trial.

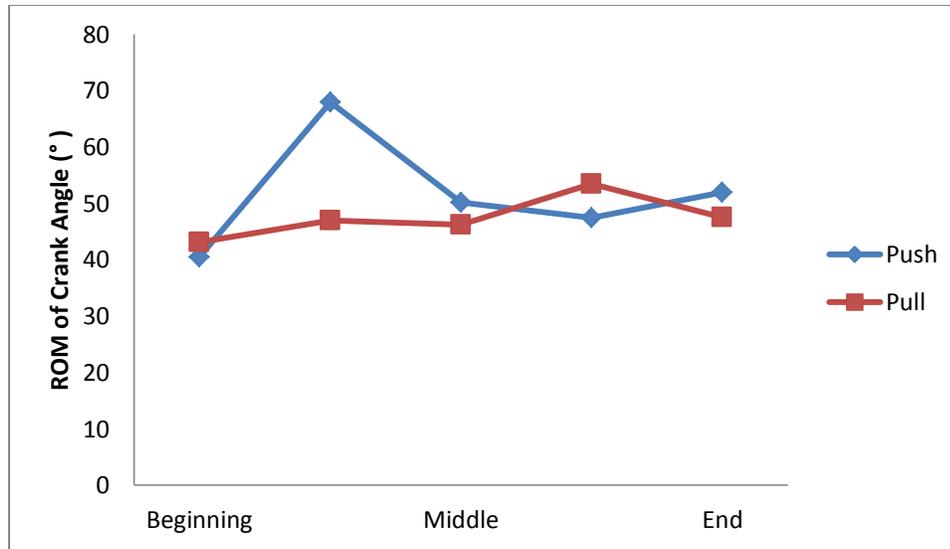


Figure 15 - Comparison of ROP of crank angle where maximum push and pull forces in the BO pedal pattern for untrained subjects;

ROP: Range of Position; BO: Backward only.

In the backward pedal pattern, highly significant differences ($p \leq 0.01$) between trained and untrained subjects were observed in the first quarter of the trial on the range of the maximum push forces (see Figure 16), and at the end of the maximum pull forces in the BO pedal pattern (see Figure 17).

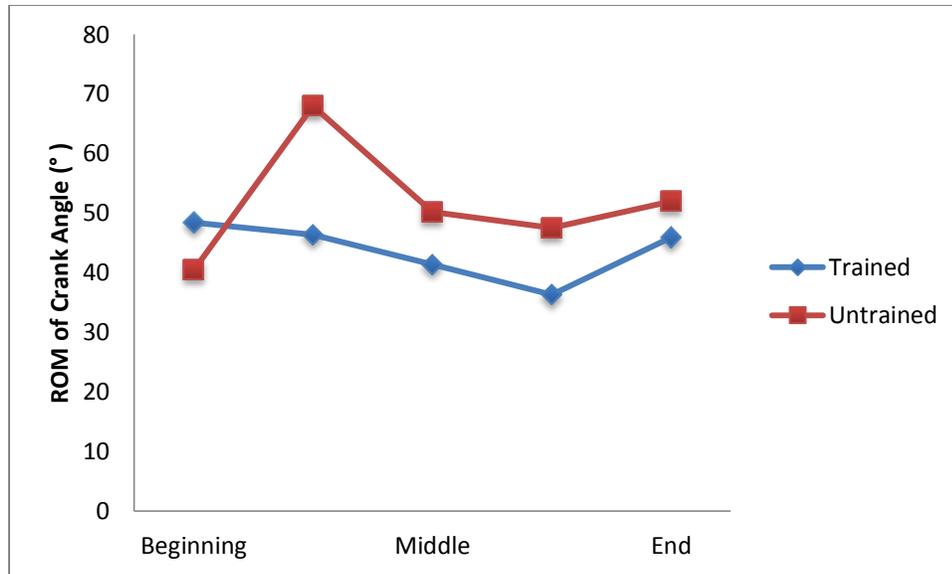


Figure 16 - Comparison of ROP between trained and untrained subjects of maximum push force of the BO pedal pattern;
 ROP: Range of Position; BO: Backward only.

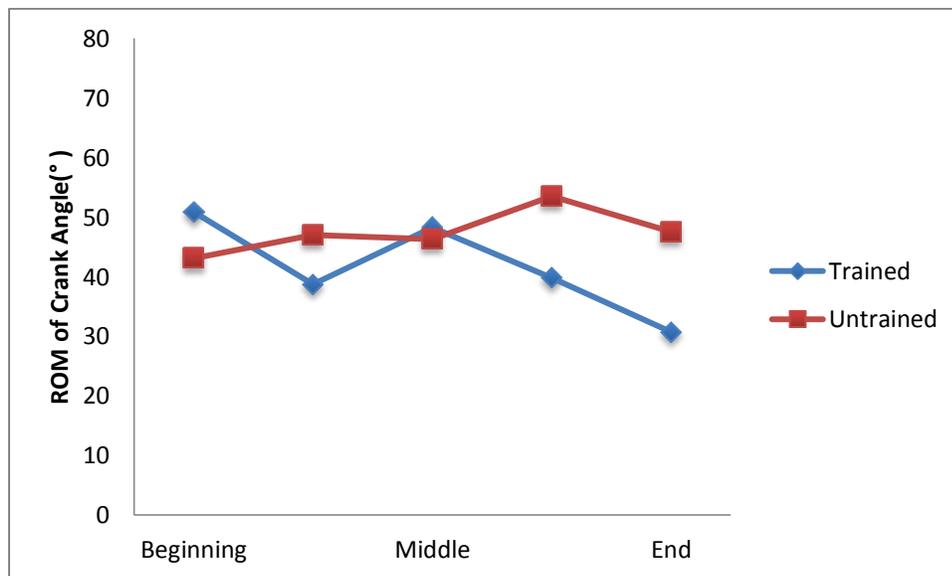


Figure 17 - Comparison of ROP between trained and untrained subjects of maximum pull force of the BO pedal pattern;
 ROP: Range of Position; BO: Backward only.

Trained subjects had highly significant differences ($p \leq 0.01$) comparing the ROP of the maximum push force in the FO and BO pedal patterns, with a significant difference ($p \leq 0.05$) found at the end of the trial (see Figure 18).

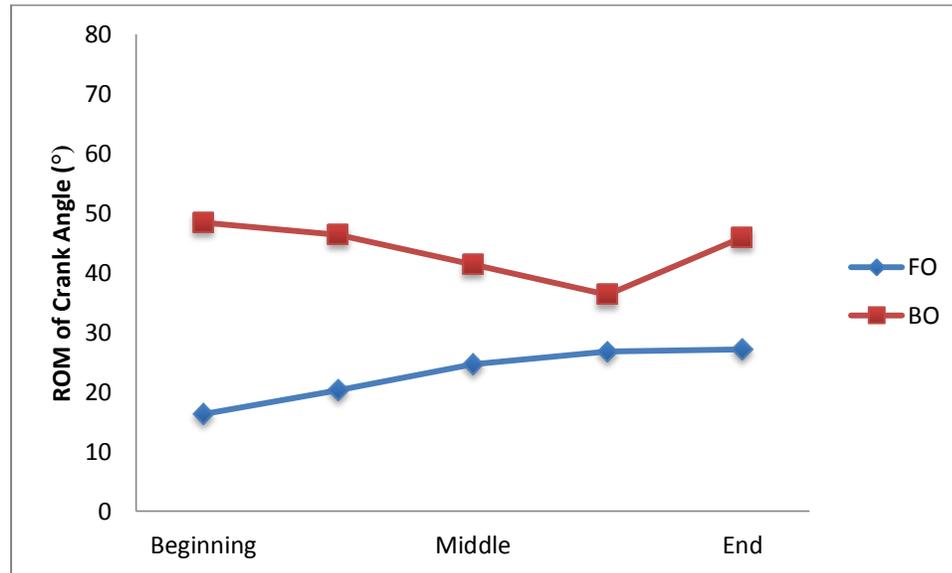


Figure 18 - Comparison of the ROP of the crank angle in the FO and BO pedal patterns for the maximum push force for trained subjects;

ROP: Range of Position; FO : Forward only; BO: Backward only.

Trained subjects also showed highly significant ($p \leq 0.01$) differences in ROP at the beginning of the trial, and a significant difference ($p \leq 0.05$) was observed at the third quarter of the trials for the maximum pull forces (see Figure 19).

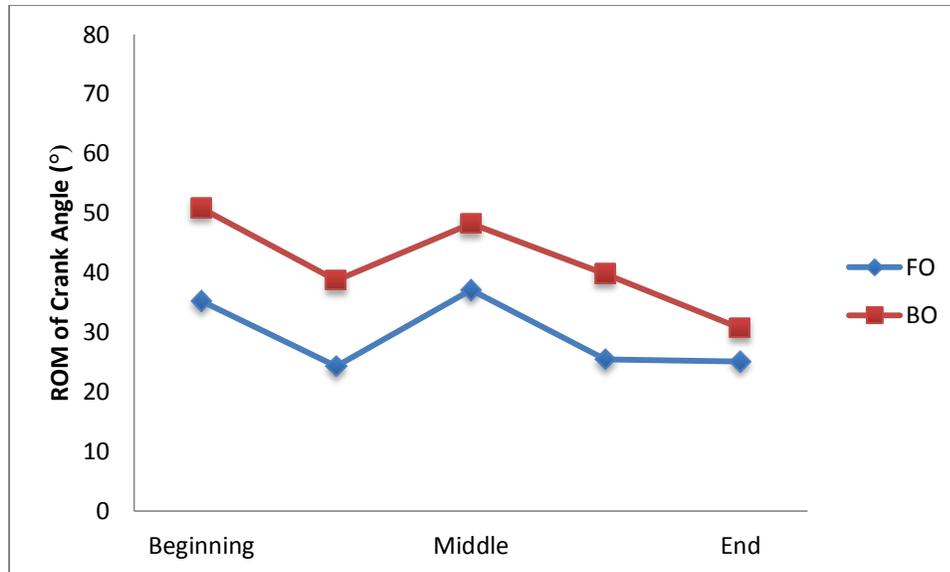


Figure 19 - Comparison of the ROP of the crank angle in the FO and BO pedal patterns for the maximum pull force for trained subjects;

ROP: Range of Position; FO : Forward only; BO: Backward only.

Untrained subjects had similar differences in the ROP of maximum push forces between FO and BO pedal patterns as we saw in trained subjects; the first half of the trial saw highly significant differences ($p \leq 0.01$) between the ROP of the maximum forces in the FO and BO pedal patterns.

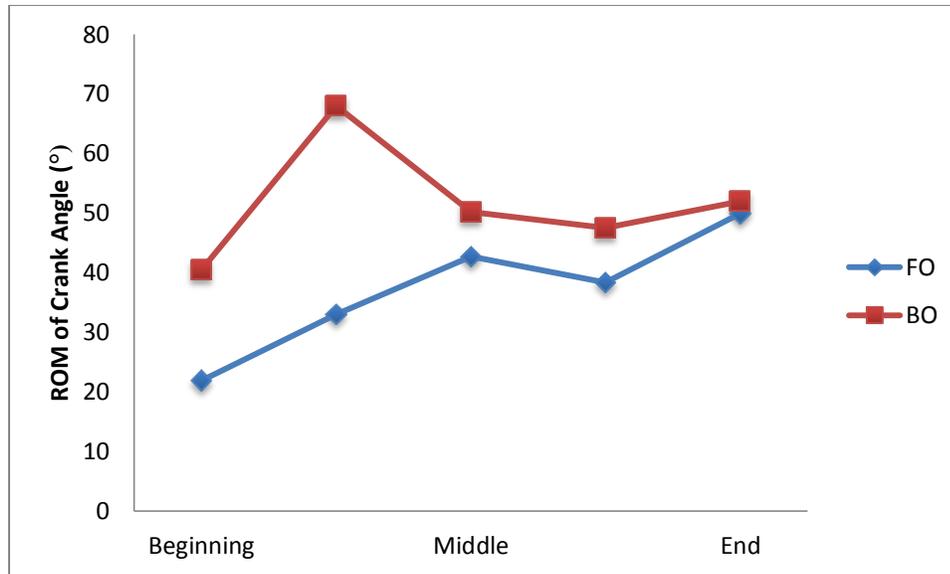


Figure 20 - Comparison of the ROP of the crank angle in the FO and BO pedal patterns for the maximum push force for untrained subjects;

ROP: Range of Position; FO : Forward only; BO: Backward only.

Untrained subjects showed significant differences ($p \leq 0.05$) in the ROP of maximum pull forces when comparing the FO and BO pedal patterns at the beginning of the trial and at the third quarter.

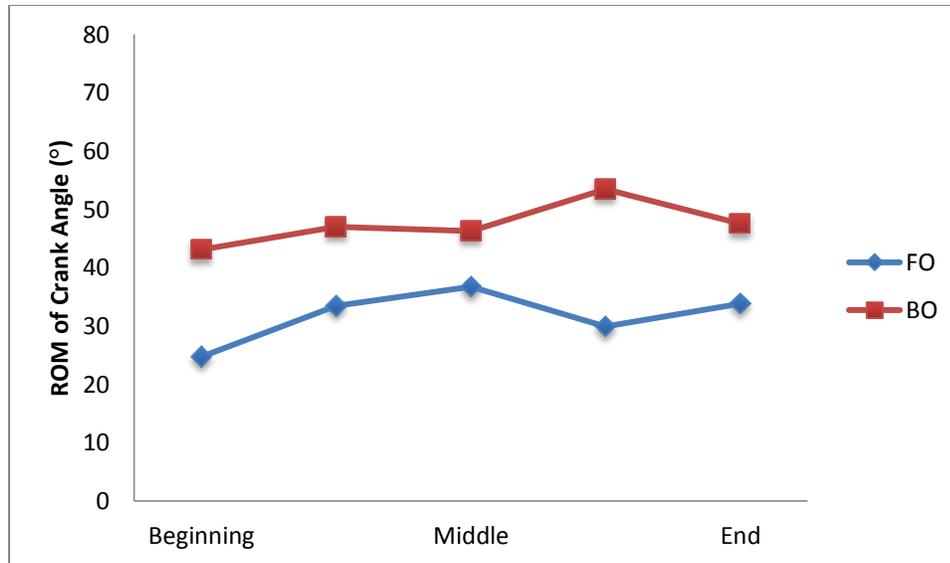


Figure 21- Comparison of the ROP of the crank angle in the FO and BO pedal patterns for the maximum push force for untrained subjects;

ROP: Range of Position; FO : Forward only; BO: Backward only.

Kinematics

Kinematic measurements included measurements of range of motion (ROM) of the hip, knee, horizontal and vertical ankle joints.

In trained subjects in the FO pedal pattern, the ROM of the maximum push force of the knee had an increase of 0.21% from the beginning to the end of the trial. There was a ROM of $9.28 \pm 7.48^\circ$ at the beginning of the trial, then after the first quarter the ROM was $6.73 \pm 6.08^\circ$, then $9.19 \pm 7.37^\circ$ at the half-way point, then $11.43 \pm 11.21^\circ$ after the third quarter, and $9.30 \pm 8.64^\circ$ at the end of the trial.

The ROM of the ankle in the horizontal direction had an overall increase of 22.34% from the beginning to the end of the trial. There was a ROM of $10.24 \pm 7.07^\circ$ at the beginning of the trial, then after the first quarter the ROM was $10.05 \pm 9.16^\circ$, then

11.74±8.73° at the half-way point, then 12.62±8.66° after the third quarter, and 12.52±9.92° at the end of the trial.

The ROM of the ankle in the vertical direction had an overall increase of 46.43% from the beginning to the end of the trial. There was a ROM of 4.95±4.81° at the beginning of the trial, then after the first quarter the ROM was 5.12±5.76°, then 5.49±4.69° at the half-way point, then 7.44±6.78° after the third quarter, and 7.25±8.62° at the end of the trial. None of the changes in the ROM for the joint angles below were significant ($p>0.05$).

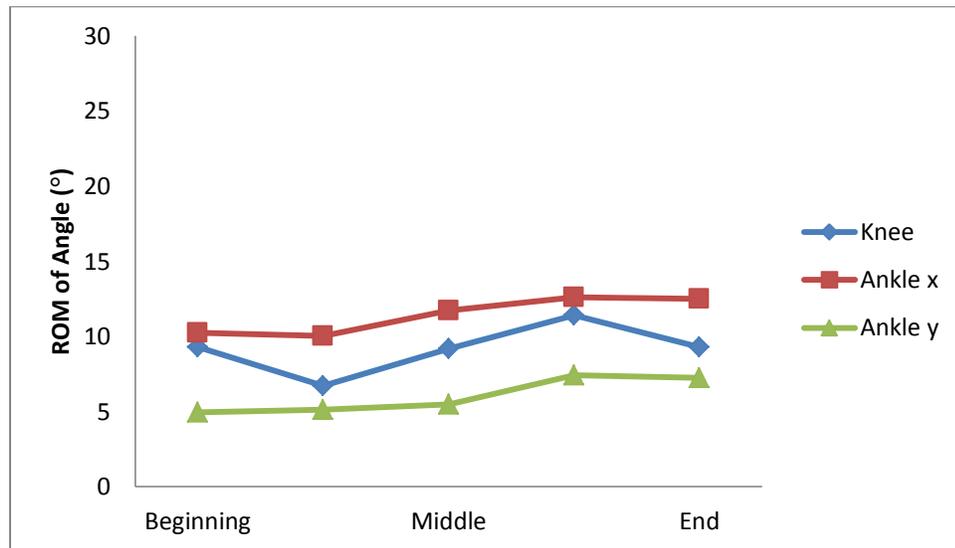


Figure 22 - Comparison of ROM of joint angles for the knee and ankle in the horizontal (x) and vertical direction (y) at the maximum push force of trained subjects FO pedal pattern;

ROM: Range of Motion; FO: Forward only.

In trained subjects in the FO pedal pattern, the ROM of the maximum pull force of the knee had a decrease of 16.81% from the beginning to the end of the trial. There was a

ROM of $12.71 \pm 7.54^\circ$ at the beginning of the trial, then after the first quarter the ROM was $11.78 \pm 7.63^\circ$, then $13.10 \pm 7.07^\circ$ at the half-way point, then $12.04 \pm 8.84^\circ$ after the third quarter, and $10.58 \pm 6.29^\circ$ at the end of the trial.

The ankle in the horizontal direction had an overall increase of 9.15% from the beginning to the end of the trial. There was a ROM of $11.49 \pm 7.74^\circ$ at the beginning of the trial, then after the first quarter the ROM was $10.26 \pm 6.22^\circ$, then $10.65 \pm 6.79^\circ$ at the half-way point, then $12.25 \pm 7.13^\circ$ after the third quarter, and $12.54 \pm 6.71^\circ$ at the end of the trial.

The ankle in the vertical direction had an overall increase of 7.43% from the beginning to the end of the trial. There was a ROM of $3.80 \pm 4.02^\circ$ at the beginning of the trial, then after the first quarter the ROM $3.14 \pm 3.12^\circ$, then $2.86 \pm 2.62^\circ$ at the half-way point, then $3.95 \pm 2.96^\circ$ after the third quarter, and $4.08 \pm 3.63^\circ$ at the end of the trial. None of the changes in the ROM for the joint angles below were significant ($p > 0.05$).

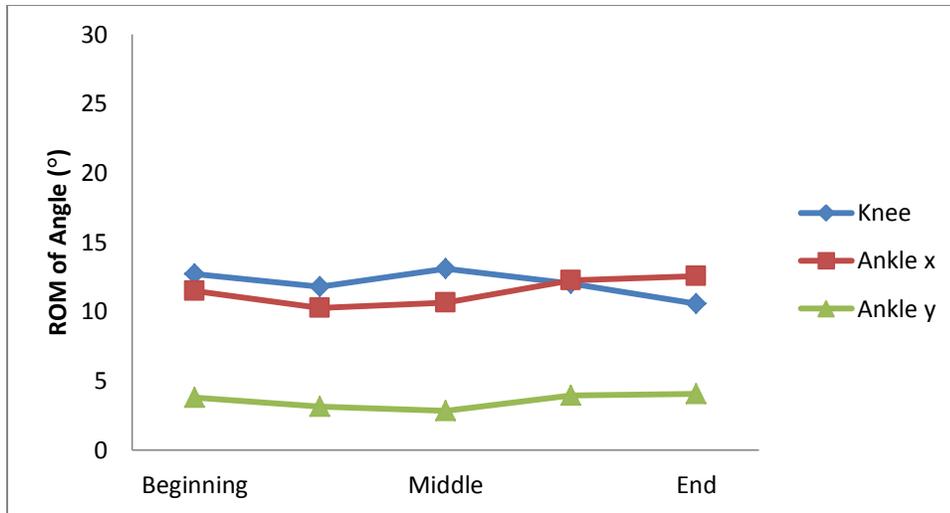


Figure 23 - Comparison of ROM of joint angles for the knee and ankle in the horizontal (x) and vertical direction (y) at the maximum pull force of trained subjects FO pedal pattern;

ROM: Range of Motion; FO: Forward only.

In untrained subjects in the FO pedal pattern, the ROM of the push force of the knee had an increase of 62.93% from the beginning to the end of the trial. There was a ROM of $8.44 \pm 6.01^\circ$ at the beginning of the trial, then after the first quarter the ROM was $10.70 \pm 5.99^\circ$, then $13.69 \pm 8.89^\circ$ at the half-way point, then $13.51 \pm 8.58^\circ$ after the third quarter, and $13.75 \pm 9.10^\circ$ at the end of the trial.

The ankle in the horizontal direction had an overall increase of 87.27% from the beginning to the end of the trial. There was a ROM of $8.60 \pm 5.28^\circ$ at the beginning of the trial, then after the first quarter the ROM was $10.77 \pm 5.29^\circ$, then $11.67 \pm 7.45^\circ$ at the half-way point, then $11.07 \pm 5.29^\circ$ after the third quarter, and $16.10 \pm 10.29^\circ$ at the end of the trial.

The ankle in the vertical direction had an overall increase of 127.74% from the beginning to the end of the trial. There was a ROM of $4.08 \pm 5.15^\circ$ at the beginning of the trial, then after the first quarter the ROM was $4.89 \pm 4.74^\circ$, then $5.61 \pm 6.86^\circ$ at the half-way point, then $6.09 \pm 5.63^\circ$ after the third quarter, and $9.30 \pm 10.77^\circ$ at the end of the trial.

The change in the ROM at the end of the trial compared to the beginning of the trial of the knee joint was significant ($p \leq 0.05$), the change in the ROM of the ankle joint in the horizontal direction was highly significant ($p \leq 0.01$), and the change in the ROM of the ankle joint in the vertical direction was significant ($p \leq 0.05$).

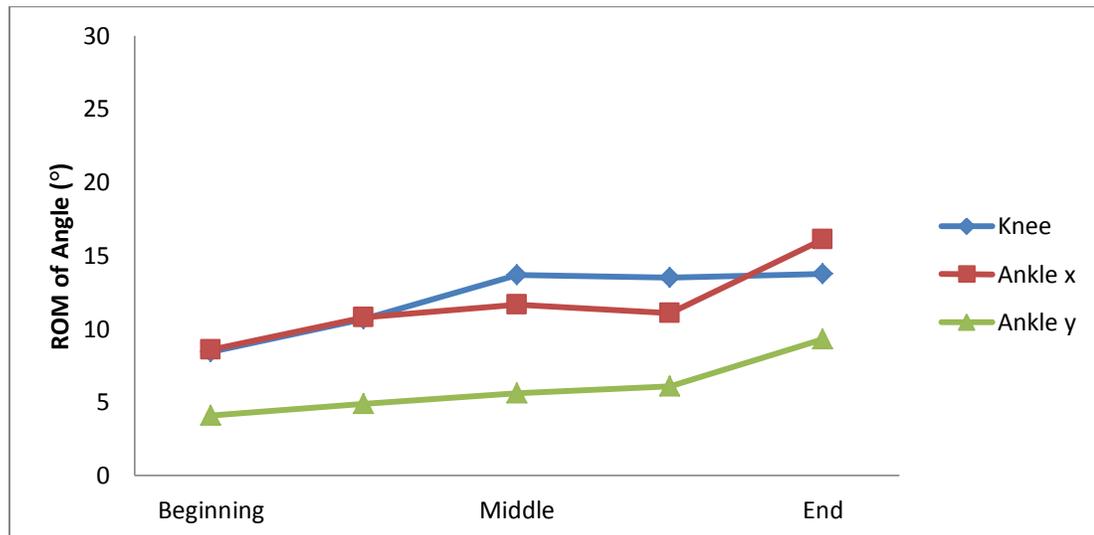


Figure 24 - Comparison of ROM of joint angles for the knee and ankle in the horizontal (x) and vertical direction (y) as the maximum push force of untrained subjects FO pedal pattern;

ROM: Range of Motion; FO: Forward only.

In untrained subjects in the FO pedal pattern, the ROM of the pull force of the knee had an increase of 42.96% from the beginning to the end of the trial. There was a ROM

of $8.92 \pm 6.52^\circ$ at the beginning of the trial, then after the first quarter the ROM was $9.61 \pm 6.35^\circ$, then $12.30 \pm 8.59^\circ$ at the half-way point, then $11.87 \pm 8.63^\circ$ after the third quarter, and $12.75 \pm 7.63^\circ$ at the end of the trial.

The ankle in the horizontal direction had an overall increase of 39.82% from the beginning to the end of the trial. There was a ROM of $8.43 \pm 7.74^\circ$ at the beginning of the trial, then after the first quarter the ROM was $11.25 \pm 4.10^\circ$, then $13.26 \pm 8.51^\circ$ at the half-way point, then $11.14 \pm 4.84^\circ$ after the third quarter, and $11.79 \pm 5.35^\circ$ at the end of the trial.

The ankle in the vertical direction had an overall decrease of 13.59% from the beginning to the end of the trial. There was a ROM of $4.82 \pm 6.96^\circ$ at the beginning of the trial, then after the first quarter the ROM was $4.85 \pm 3.62^\circ$, then $5.90 \pm 7.20^\circ$ at the half-way point, then $4.63 \pm 2.90^\circ$ after the third quarter, and $4.17 \pm 2.62^\circ$ at the end of the trial. None of the changes in the ROM for the joint angles below were significant ($p > 0.05$).

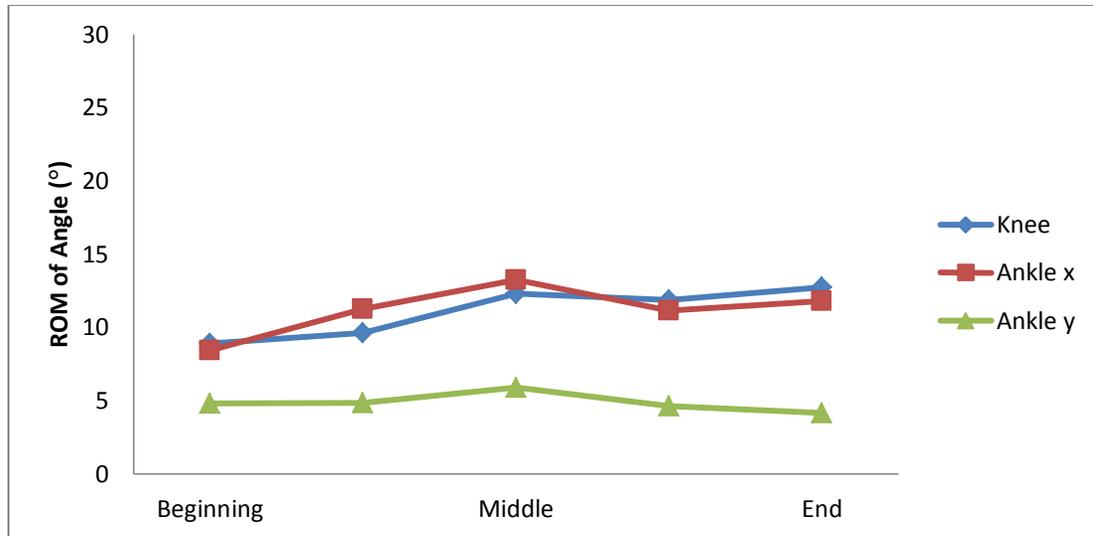


Figure 25 - Comparison of ROM of joint angles for the knee and ankle in the horizontal (x) and vertical direction (y) of the maximum pull force of untrained subjects FO pedal pattern;

ROM: Range of Motion; FO: Forward only.

In trained subjects in the BO pedal pattern, the ROM of the push force of the knee had an increase of 6.70% in ROM from the beginning to the end of the trial. There was a ROM of $24.68 \pm 13.13^\circ$ at the beginning of the trial, then after the first quarter the ROM was $21.80 \pm 10.66^\circ$, then $19.00 \pm 15.58^\circ$ at the half-way point, then $15.14 \pm 9.90^\circ$ after the third quarter, and $26.33 \pm 16.49^\circ$ at the end of the trial.

The ROM of the ankle in the horizontal direction had an overall increase of 11.73% from the beginning to the end of the trial. There was a ROM of $12.16 \pm 9.32^\circ$ at the beginning of the trial, then after the first quarter the ROM was $14.22 \pm 8.25^\circ$, then $9.77 \pm 4.61^\circ$ at the half-way point, then $9.35 \pm 4.02^\circ$ after the third quarter, and $13.58 \pm 6.62^\circ$ at the end of the trial.

The ROM of the ankle in the vertical direction had an overall increase of 47.11% from the beginning to the end of the trial. There was a ROM of $5.31 \pm 6.84^\circ$ at the beginning of the trial, then after the first quarter the ROM was $5.11 \pm 5.63^\circ$, then $5.06 \pm 4.99^\circ$ at the half-way point, then $4.58 \pm 3.77^\circ$ after the third quarter, and $7.81 \pm 6.60^\circ$ at the end of the trial.

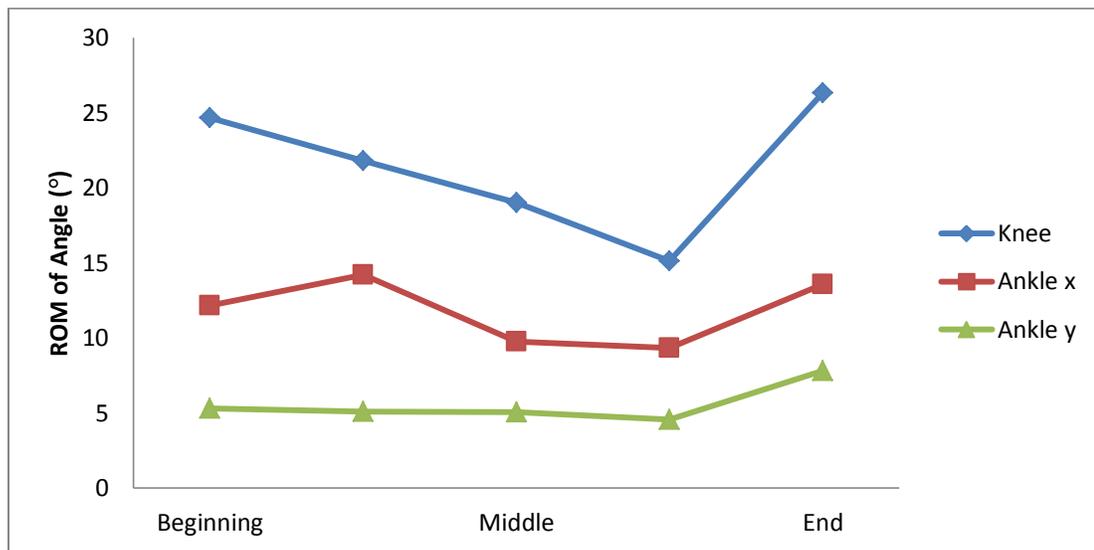


Figure 26 - Comparison of ROM of joint angles for the knee and ankle in the horizontal (x) and vertical direction (y) at the maximum push force of trained subjects BO pedal pattern;

ROM: Range of Motion; BO: Backward only.

In trained subjects in the BO pedal pattern, the ROM of the pull force of the knee had a decrease of 16.22% in ROM from the beginning to the end of the trial. There was a ROM of $17.95 \pm 14.70^\circ$ at the beginning of the trial, then after the first quarter the ROM was $15.95 \pm 13.27^\circ$, then $22.17 \pm 16.31^\circ$ at the half-way point, then $17.15 \pm 8.98^\circ$ after the third quarter, and $15.04 \pm 9.86^\circ$ at the end of the trial.

The ROM of the ankle in the horizontal direction had an overall increase of 6.34% from the beginning to the end of the trial. There was a ROM of $13.36 \pm 9.18^\circ$ at the beginning of the trial, then after the first quarter the ROM was $13.73 \pm 9.41^\circ$, then $15.14 \pm 6.43^\circ$ at the half-way point, then $11.86 \pm 9.34^\circ$ after the third quarter, and $14.20 \pm 10.16^\circ$ at the end of the trial.

The ROM of the ankle in the vertical direction had an overall increase of 45.88% from the beginning to the end of the trial. There was a ROM of $5.25 \pm 6.50^\circ$ at the beginning of the trial, then after the first quarter the ROM was $5.89 \pm 9.95^\circ$, then $8.22 \pm 6.85^\circ$ at the half-way point, then $6.38 \pm 7.26^\circ$ after the third quarter, and $7.66 \pm 9.24^\circ$ at the end of the trial. None of the changes in the ROM for the joint angles below were significant ($p > 0.05$).

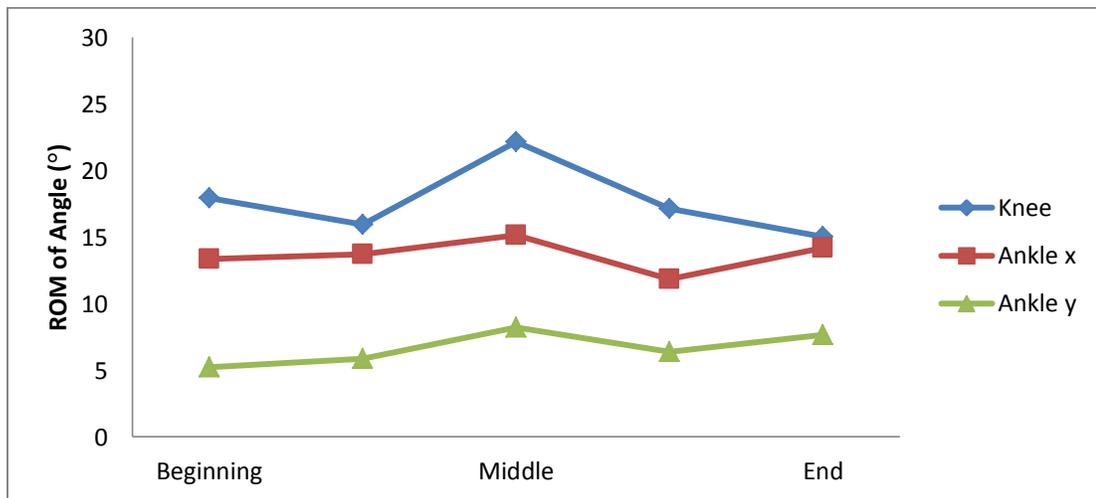


Figure 27 - Comparison of ROM of joint angles for the knee and ankle in the horizontal (x) and vertical direction (y) at the maximum pull force of trained subjects BO pedal pattern;

ROM: Range of Motion; BO: Backward only.

In untrained subjects in the BO pedal pattern, the ROM of the push force of the knee had a decrease of 9.64% in ROM from the beginning to the end of the trial. There was a ROM of $16.59 \pm 11.07^\circ$ at the beginning of the trial, then after the first quarter the ROM was $11.88 \pm 7.21^\circ$, then $19.80 \pm 15.15^\circ$ at the half-way point, then $15.07 \pm 13.01^\circ$ after the third quarter, and $14.99 \pm 11.60^\circ$ at the end of the trial.

The ROM of the ankle in the horizontal direction had an overall decrease of 8.14% from the beginning to the end of the trial. There was a ROM of $13.05 \pm 4.89^\circ$ at the beginning of the trial, then after the first quarter the ROM was $26.84 \pm 7.36^\circ$, then $13.34 \pm 7.47^\circ$ at the half-way point, then $14.21 \pm 5.37^\circ$ after the third quarter, and $11.99 \pm 5.38^\circ$ at the end of the trial.

The ROM of the ankle in the vertical direction had an overall increase of 17.14% from the beginning to the end of the trial. There was a ROM of $5.74 \pm 5.50^\circ$ at the beginning of the trial, then after the first quarter the ROM was $16.69 \pm 4.66^\circ$, then $6.22 \pm 5.35^\circ$ at the half-way point, then $5.11 \pm 3.30^\circ$ after the third quarter, and $6.72 \pm 4.12^\circ$ at the end of the trial. None of the changes in the ROM for the joint angles below were significant ($p > 0.05$).

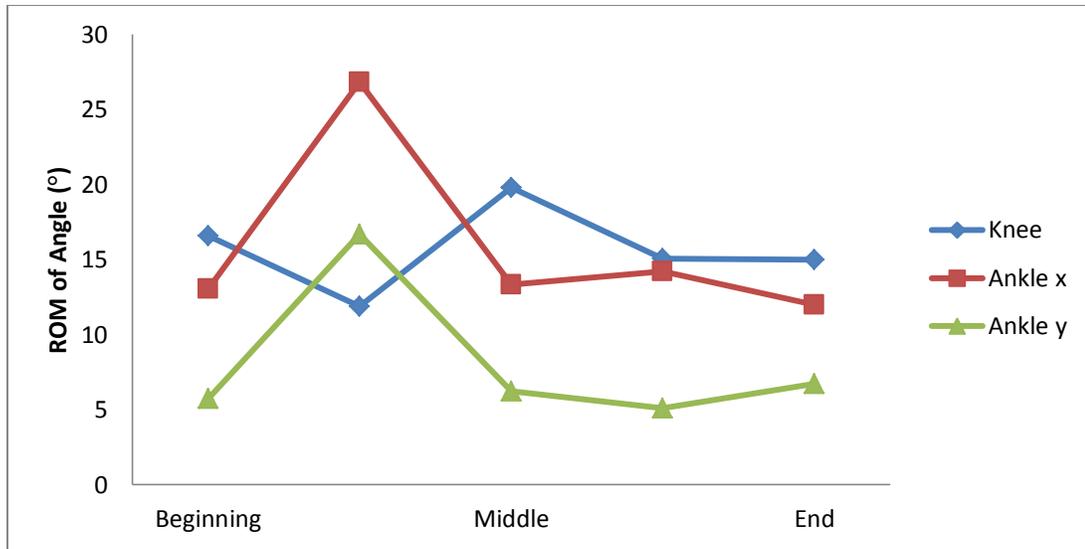


Figure 28 - Comparison of ROM of joint angles for the knee and ankle in the horizontal (x) and vertical direction (y) of the maximum push force of untrained subjects BO pedal pattern;

ROM: Range of Motion; BO: Backward only.

In untrained subjects in the BO pedal pattern, the ROM of the pull force of the knee had a decrease of 15.90% in ROM from the beginning to the end of the trial. There was a ROM of $16.28 \pm 15.20^\circ$ at the beginning of the trial, then after the first quarter the ROM was $7.70 \pm 5.74^\circ$, then $13.46 \pm 13.60^\circ$ at the half-way point, then $14.29 \pm 12.95^\circ$ after the third quarter, and $13.69 \pm 10.06^\circ$ at the end of the trial.

The ROM of the ankle in the horizontal direction had an overall increase of 6.27% from the beginning to the end of the trial. There was a ROM of $13.04 \pm 10.58^\circ$ at the beginning of the trial, then after the first quarter the ROM was $16.85 \pm 12.39^\circ$, then $10.71 \pm 7.01^\circ$ at the half-way point, then $12.46 \pm 7.36^\circ$ after the third quarter, and $13.86 \pm 5.81^\circ$ at the end of the trial.

The ROM of the ankle in the vertical direction had an overall decrease of 31.86% from the beginning to the end of the trial. There was a ROM of $7.87 \pm 10.17^\circ$ at the beginning of the trial, then after the first quarter the ROM was $9.69 \pm 1.85^\circ$, then $5.82 \pm 3.59^\circ$ at the half-way point, then $7.68 \pm 4.48^\circ$ after the third quarter, and $5.36 \pm 2.64^\circ$ at the end of the trial. None of the changes in the ROM for the joint angles below were significant ($p > 0.05$).

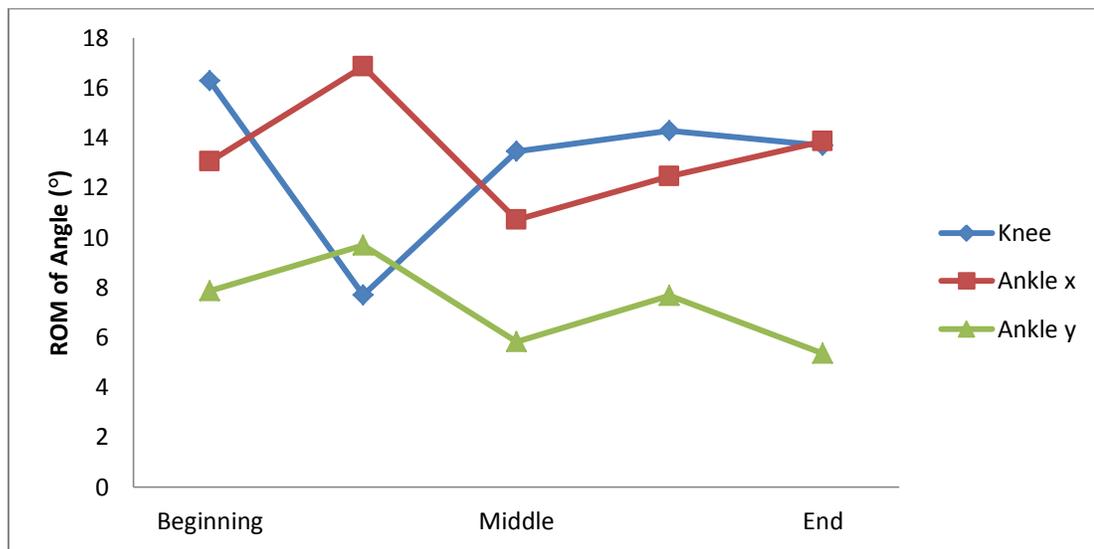


Figure 29 - Comparison of ROM of joint angles for the knee and ankle in the horizontal (x) and vertical direction (y) at the maximum pull force of untrained subjects BO pedal pattern;

ROM: Range of Motion; BO: Backward only.

The hip ROM followed a different trend in trained compared with untrained subjects for both FO and BO pedal patterns, in both the push and the pull on each pedal pattern.

In the FO pedal pattern for the push forces, the ROM of the hip differed between trained and untrained subjects. Trained subjects had an overall decrease in hip ROM by 25.43%, whereas untrained subjects had an overall increase of 45.20% in hip ROM. In the beginning of the trial, trained and untrained subjects had a 25.30% difference in ROM, trained subjects having a greater ROM, and ended at a 45.45% difference with untrained subjects having the greater ROM. These differences were significant ($p \leq 0.05$).

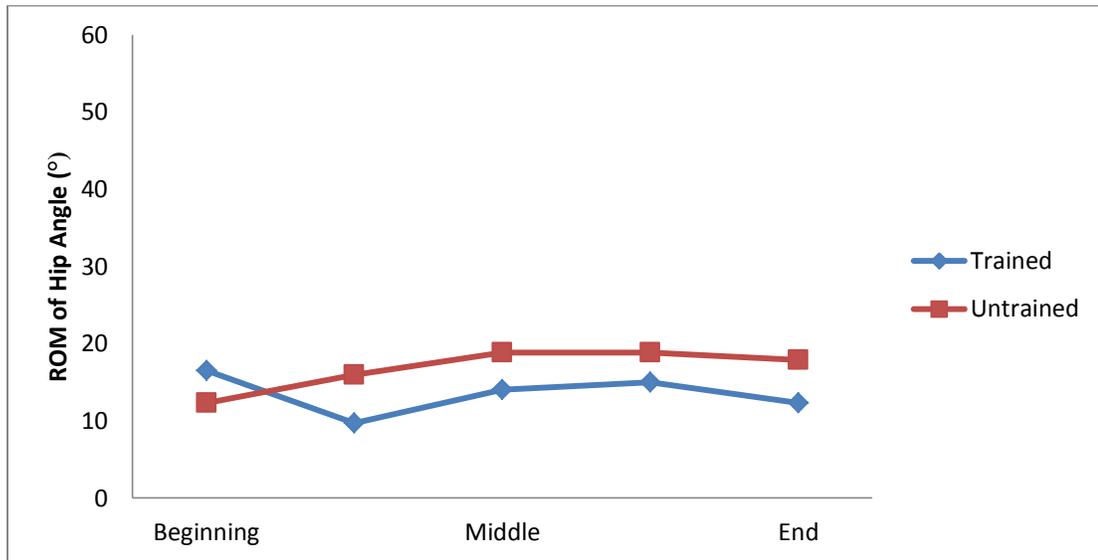


Figure 30 - Comparison of ROM of hip joint between trained and untrained subjects at maximum push force of the FO pedal pattern;

ROM: range of motion; FO: Forward only.

In the FO pedal pattern for the pull forces, the ROM of the hip differed between trained and untrained subjects. Trained subjects had an overall decrease in hip ROM by 30.78%, whereas untrained subjects had an overall increase of 12.76% in hip ROM. In the beginning of the trial, trained and untrained subjects had a 6.09% difference in ROM, untrained subjects having a greater ROM, and ended at a 72.81% difference with

untrained subjects still having the greater ROM. These differences were highly significant ($p \leq 0.01$).

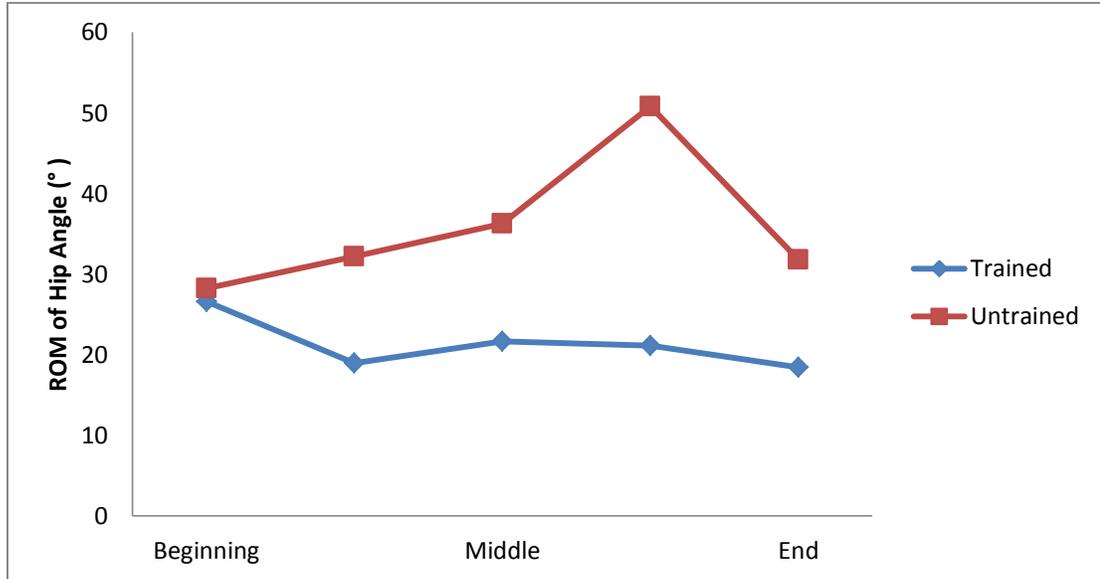


Figure 31 - Comparison of ROM of hip joint between trained and untrained subjects at maximum pull force of the FO pedal pattern;

ROM: range of motion; FO: Forward only.

In the BO pedal pattern for the push forces, the ROM of the hip differed between trained and untrained subjects. Trained subjects had an overall decrease in hip ROM by 21.86%, whereas untrained subjects had an overall increase of 42.31% in hip ROM. In the beginning of the trial, trained and untrained subjects had a 41.67% difference in ROM, trained subjects having a greater ROM, and ended at a 6.23% difference with untrained subjects having the greater ROM.

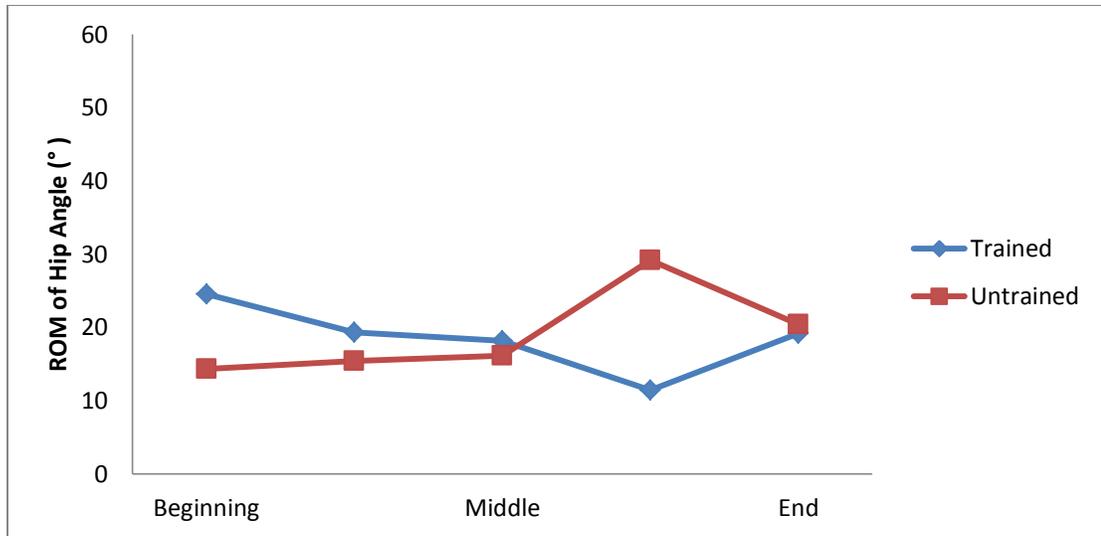


Figure 32- Comparison of ROM of hip joint between trained and untrained subjects at maximum push force of the BO pedal pattern;
 ROM: range of motion; BO: Backward only.

In the BO pedal pattern for the pull forces, the ROM of the hip differed between trained and untrained subjects. Trained subjects had an overall decrease in hip ROM by 41.08%, whereas untrained subjects had an overall increase of 36.94% in hip ROM. In the beginning of the trial, trained and untrained subjects had a 33.65% difference in ROM, trained subjects having a greater ROM, and ended at a 54.20% difference with untrained subjects having the greater ROM.

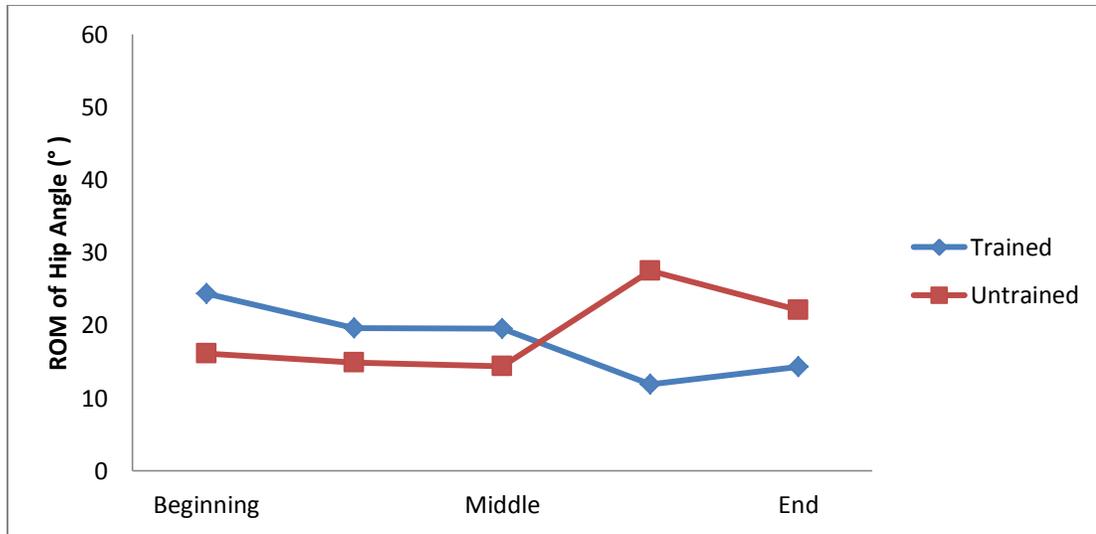


Figure 33 - Comparison of ROM of hip joint between trained and untrained subjects at maximum pull force of the BO pedal pattern;

ROM: range of motion; BO: backward only.

The ROM for the hip reacted opposite in trained compared to untrained subjects for both the push and the pull of the BO pedal pattern. These differences in ROM were not significant ($p>0.05$).

When comparing the ROM of knee and ankle joints of trained and untrained subjects between the FO and BO pedal patterns, highly significant differences ($p\leq 0.01$) were observed at the beginning, the first quarter, and at the end points for only the knee joint in the push portion of the revolution. The middle point was also significant ($p\leq 0.05$) (see Figure 34). All other differences observed in the knee and ankle joints were not significant ($p>0.05$) for both trained and untrained subjects. However, the other joints for both trained and untrained showed a similar pattern in that as the ROM increases or decreases for one pedal pattern, it has the opposite effect for the other pedal pattern (see Figure 34).

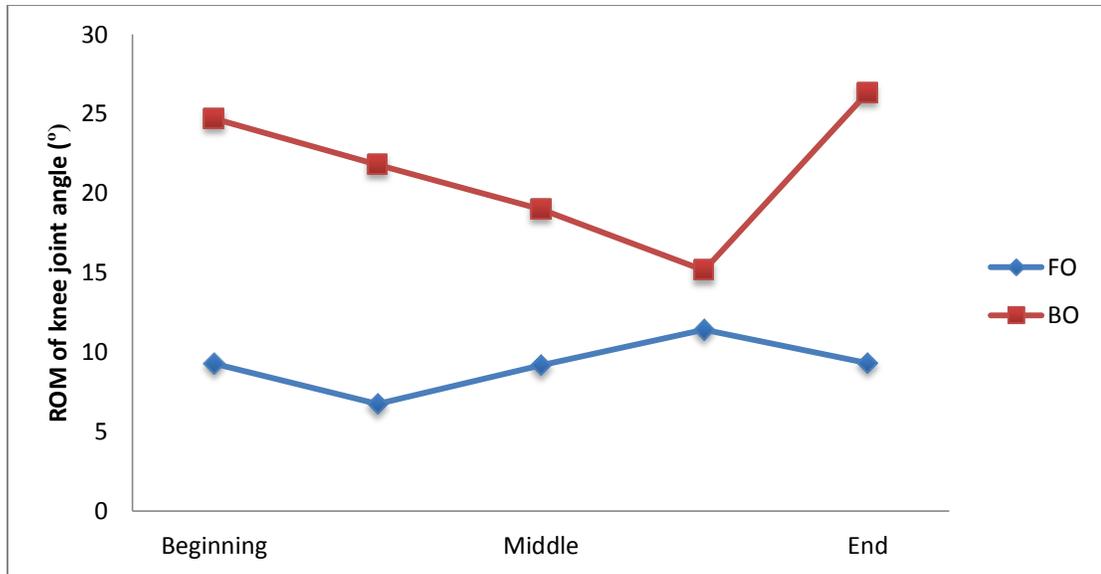


Figure 34 - Comparison of the ROM of the knee joint angle at the maximum push force between FO and BO pedal patterns for trained subjects;

ROM: Range of Motion; FO: Forward only; BO: Backward only.

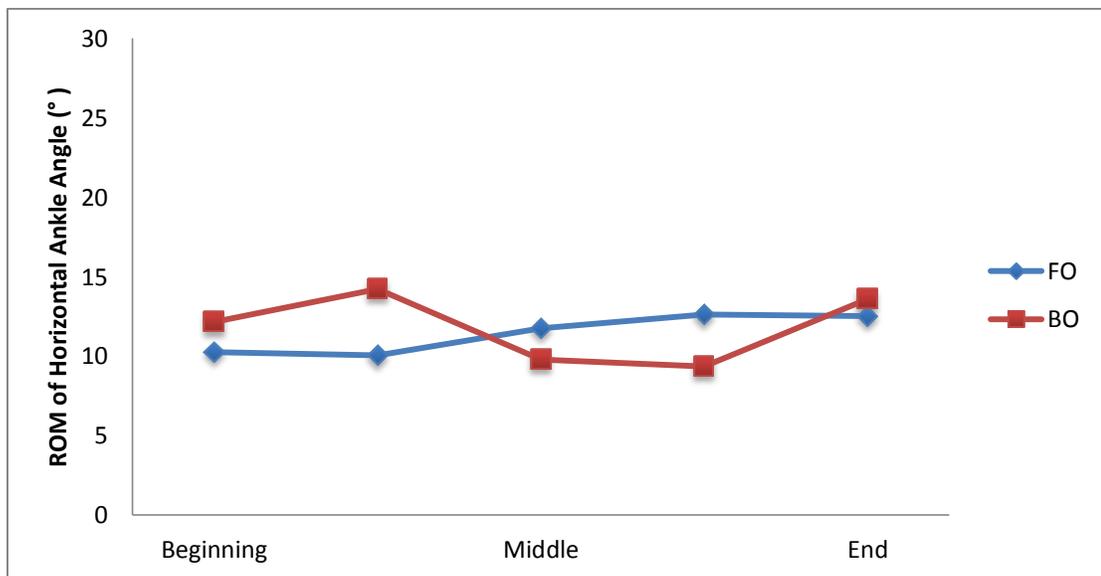


Figure 35 - Comparison of the ROM of the horizontal ankle joint angle at the maximum push force between FO and BO pedal patterns for trained subjects;

ROM: Range of Motion; FO: Forward only; BO: Backward only.

Muscle activity

Data collected from the EMG, including the median power frequency (MPF) values, as well as the relative muscle activation levels as compared to the activation levels at the beginning of the trial, gave us insight to muscle activity.

EMG

There were some surprising observations in the values observed from the EMG. MPF did not show any significant ($p>0.05$) results from the beginning to the end of the trial.

Muscle activation levels

The GM and the TA showed the greatest change in activation levels among both untrained and trained subjects. Both muscles decreased in their percentage of activation levels throughout the trial as compared to the beginning of the trial in all pedal patterns, then increased at the end of the trial (see Table 1 below). Values are expressed as a percentage of the first measurement in the trial. The VL and VM also showed a decrease in activation levels, however it was not significant ($p>0.05$). The BF did not show any significant change ($p>0.05$) through the duration of the trial, and in some subjects it actually showed a small increase in activation levels.

Table 1 - A comparison of the relative activation levels based on the percentage of the activation level at the beginning of the trial of the GM and TA; G M:

gastrocmedialis; TA: tibialis anterior

FO	GM - T	GM - UT	TA - T	TA - UT
Start	100.00%	100.00%	100.00%	100.02%
1st quarter	79.18%	78.27%	85.52%	80.79%
Middle	74.51%	91.69%	38.65%	70.61%
3rd Quarter	85.45%	67.48%	46.18%	63.42%
End	90.22%	105.23%	78.71%	92.12%
BO	GM - T	GM - UT	TA - T	TA - UT
Start	100.00%	100.00%	100.00%	100.00%
1st quarter	104.82%	101.88%	68.38%	78.84%
Middle	66.93%	84.48%	51.24%	61.07%
3rd Quarter	50.16%	62.30%	45.75%	86.34%
End	68.48%	95.39%	61.88%	128.92%

Physiological response

Physiological responses include the heart rate data and BL.

Heart rate

Subjects' heart rates increased as subjects pedaled and peaked at fatigue, as expected. No surprising results were observed. There was a large increase during the first quarter since subjects started from rest, and the following three quarters saw minimal increases (see Figures 36-37).

Subject's heart rate saw similar results among trained and untrained subjects. Heart rate was measured in beats per minute (bpm). Average values across all three pedal patterns followed a similar pattern and no significant differences ($p>0.05$) were observed

among trained subjects. Average values obtained are as follows: resting heart rate of 78.98 ± 13.92 beats per minute (bpm), and 163.55 ± 17.33 bpm, 169.15 ± 15.46 bpm, 174.84 ± 11.10 bpm and 176.20 ± 13.33 bpm after the first, second, third and fourth quarters respectively. These represent increases of 107.08%, 3.42%, 3.36% and 0.78% respectively; an overall increase of 123.09% (see Figure 36).

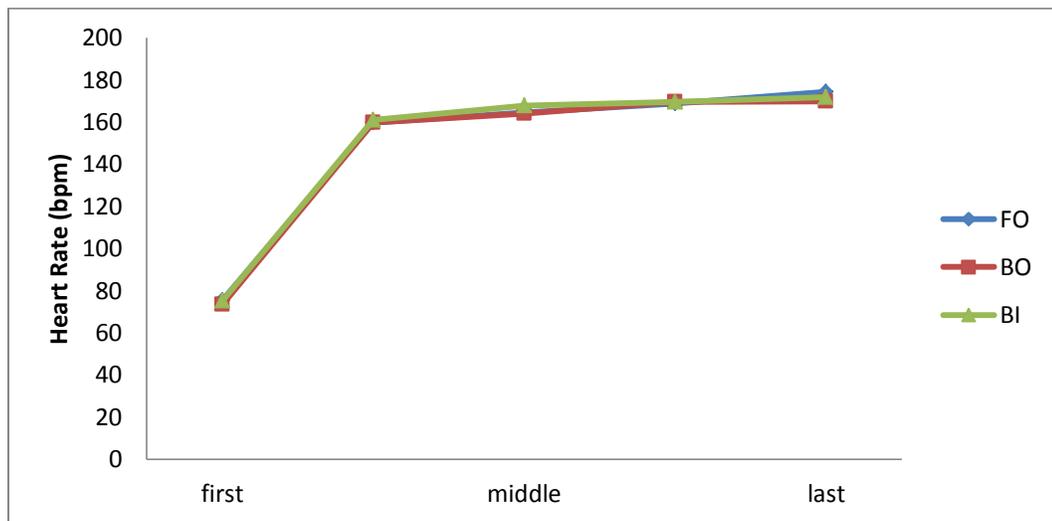


Figure 36 - Comparison of heart rate for trained subjects in all three pedal patterns;

FO: Forward only; BO: Backward only; BI: Bi-directional.

Untrained subjects heart rate in all three pedal patterns follow a similar pattern. With all three pedal patterns averaged together, untrained subjects started with a resting heart rate of 74.58 ± 14.45 bpm. The average heart rate increased to 160.15 ± 12.74 bpm, 165.54 ± 12.71 bpm, 169.28 ± 13.15 bpm and 171.98 ± 12.67 bpm after the first, second, third and fourth quarters respectively. Increases of 114.74%, 3.37%, 2.27% and 1.59% after each quarter were observed, showing an overall increase of 130.60%. There were no significant differences ($p > 0.05$) between the heart rate among the three pedal patterns ($p \geq 0.05$) (see Figure 37).

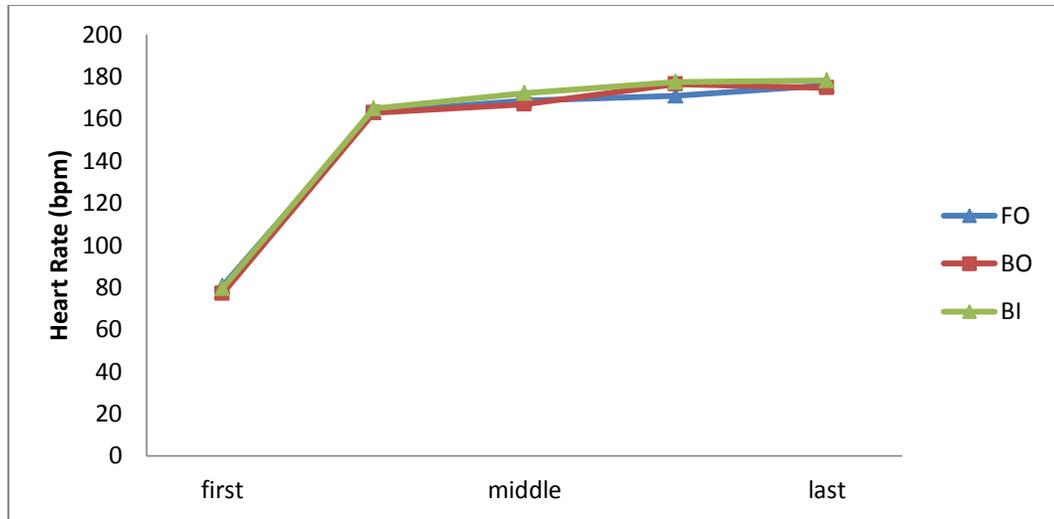


Figure 37 - Comparison of heart rate for untrained subjects in all three pedal patterns;

FO: Forward only; BO: Backward only; BI: Bi-directional.

Blood lactate

As expected, for both trained and untrained subjects, the BL increased as each trial progressed.

Trained subjects saw a delayed accumulation of lactate in the BI pedal pattern, however the FO and BO pedal patterns were similar (see Figure 38). The end levels of lactate in all three pedal patterns were similar. In the FO pedal pattern BL started at 2.79 ± 1.54 mmol/L, after the first quarter levels rose to 6.56 ± 1.94 mmol/L, at the half-way point levels were 8.67 ± 1.80 mmol/L, after three quarters levels were at 10.55 ± 2.46 mmol/L and levels peaked at 13.06 ± 3.50 mmol/L with increases of 135.41%, 32.22%, 21.59% and 23.78% respectively. The BO pedal pattern started with lactate levels of 2.04 ± 0.46 mmol/L, increasing to 6.78 ± 2.08 mmol/L after the first quarter, then to 8.39 ± 2.23 mmol/L at the end of the second quarter, 10.15 ± 1.95 mmol/L after the third and reaching fatigue at 11.13 ± 2.46 mmol/L. These are increases by 232.92%, 23.64%,

21.02% and 9.67% in the first, second, third and fourth quarters respectively. The BI pedal pattern saw lactate levels of 2.01 ± 0.80 mmol/L at the beginning, 6.81 ± 2.20 mmol/L and 9.58 ± 2.78 mmol/L after the first and second quarters (an increase of 239.27% and 40.70%) respectively, however after the third quarter I did not see a very large increase with levels at 9.87 ± 2.44 , a 3.10% increase, and end levels at 12.37 ± 3.73 mmol/L at the end, a 25.27% increase. In trained subjects, BL in the FO and BI pedal patterns were higher, FO lactate levels being significantly higher ($p \leq 0.05$; 17.28% and 11.12% respectively) at fatigue than were the lactate levels in the BO pedal pattern. BL for the BI pedal pattern increased quicker, then seemed to plateau before a final increase preceding the state of fatigue. At the middle measurement, the difference between the BL for the BI pedal pattern and the FO pedal pattern was significant ($p \leq 0.05$), and the difference between the BL between the BI pedal pattern and the BO pedal pattern at the middle measurement were highly significant ($p \leq 0.01$). Trained subjects also had significant differences ($p \leq 0.05$) in BL at the end of the trial. The difference between the end blood lactate level for the FO and the BO pedal pattern was highly significant ($p \leq 0.01$), BL in the BO pedal pattern being lower than those in the FO pedal pattern.

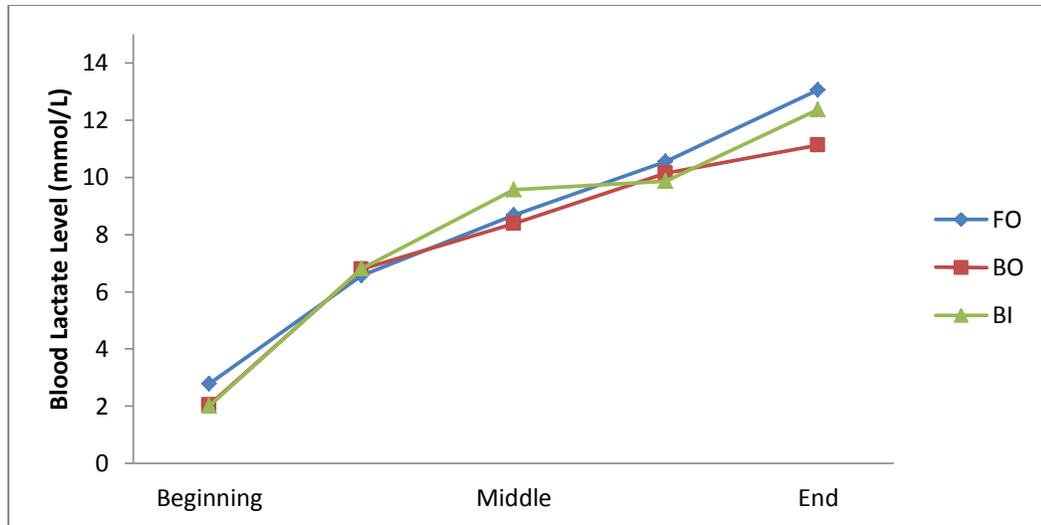


Figure 38 - Comparison of average BL for trained subjects for all three pedal patterns;

FO: Forward only; BO: Backward only; BI: Bi-directional.

A similar trend was observed for all three pedal patterns for untrained subjects (see Figure39). All three pedal patterns for untrained subjects had an average of 2.25 ± 1.06 mmol/L to start, then after the first quarter of the duration levels jumped to an average of 6.51 ± 2.47 mmol/L, at the middle they were 7.87 ± 2.36 mmol/L, at 75% duration they were at 9.67 ± 2.80 mmol/L and levels peaked at the end at 11.67 ± 2.87 mmol/L at which point subjects were fatigued. We can see that the increase is not linear. The first quarter saw a 192.40% increase from resting BL through the first quarter of their duration. The second quarter saw a 20.91% increase, and the third and fourth quarters had similar increases of 19.1% and 19.8% respectively; almost a linear pattern in the last three quarters. There were no significant differences ($p > 0.05$) between BL among these three pedal patterns in untrained subjects ($p \geq 0.05$).

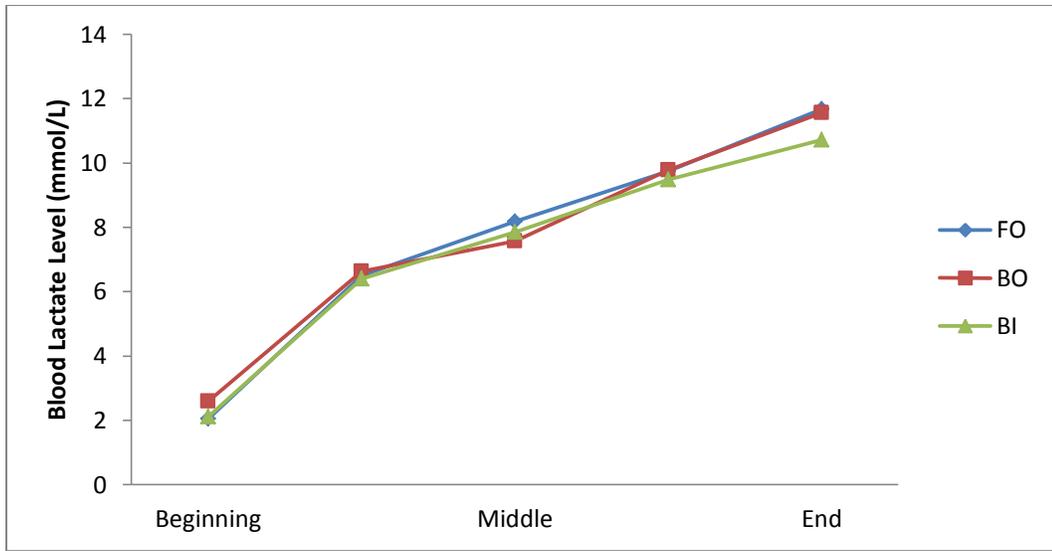


Figure 39 - Comparison of average BL for untrained subjects in all three pedal patterns;
FO: Forward only; BO: Backward only; BI: Bi-directional.

BL for trained subjects were 11.86% higher than untrained subjects at the end of the FO pedal pattern. This was not significant ($p > 0.05$).

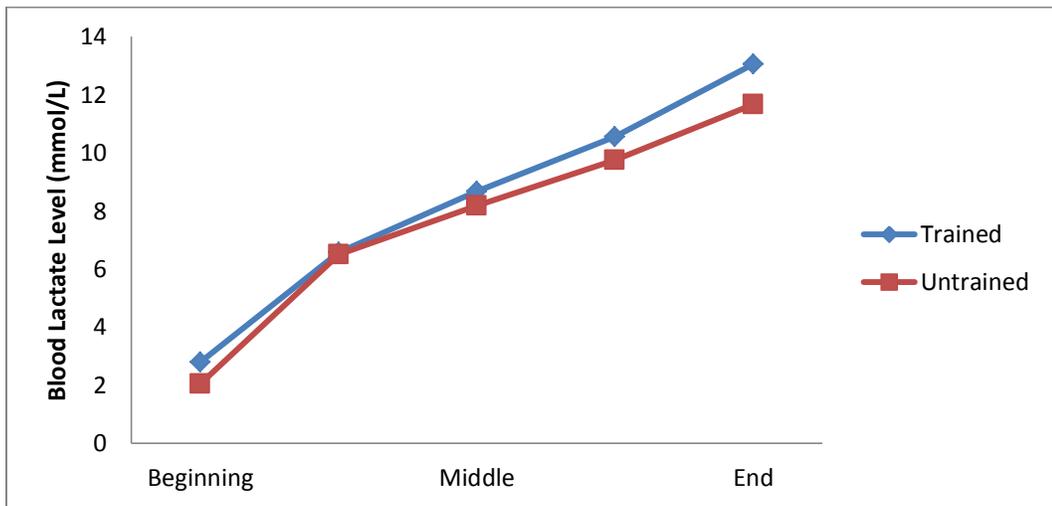


Figure 40 - Comparison of average BL between trained and untrained subjects in the FO pedal pattern;

FO: Forward only.

BL at time of fatigue in trained compared with untrained subjects in the BO pedal pattern were similar; no significant differences ($p>0.05$) were observed.

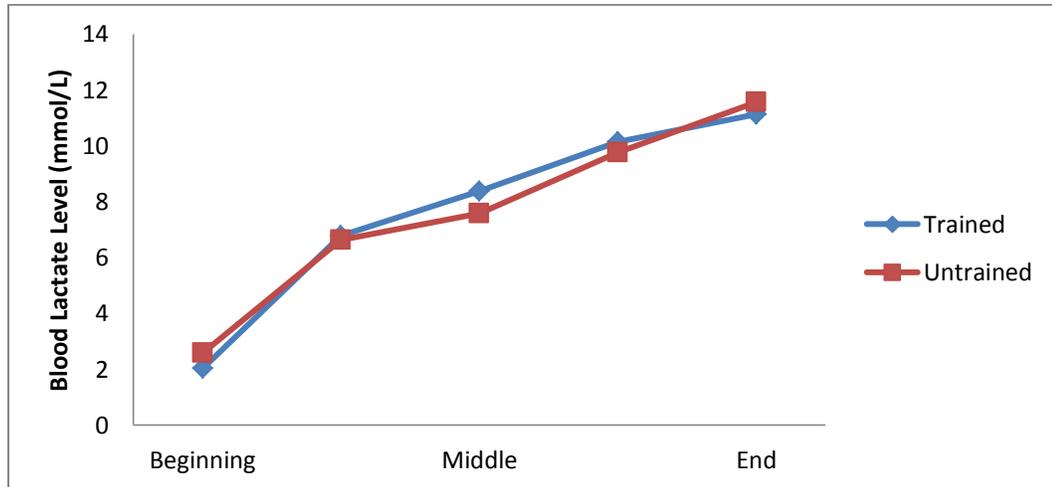


Figure 41 - Comparison of average BL between trained and untrained subjects in the BO pedal pattern;
BO: Backward only.

BL for trained subjects were 15.33% higher than untrained subjects at the end of the BI pedal pattern. This was significant ($p\leq 0.05$). However, in the middle of the trial, BL for trained subjects were found to be 21.87% higher than those found in the untrained subjects, a highly significant difference ($p\leq 0.01$).

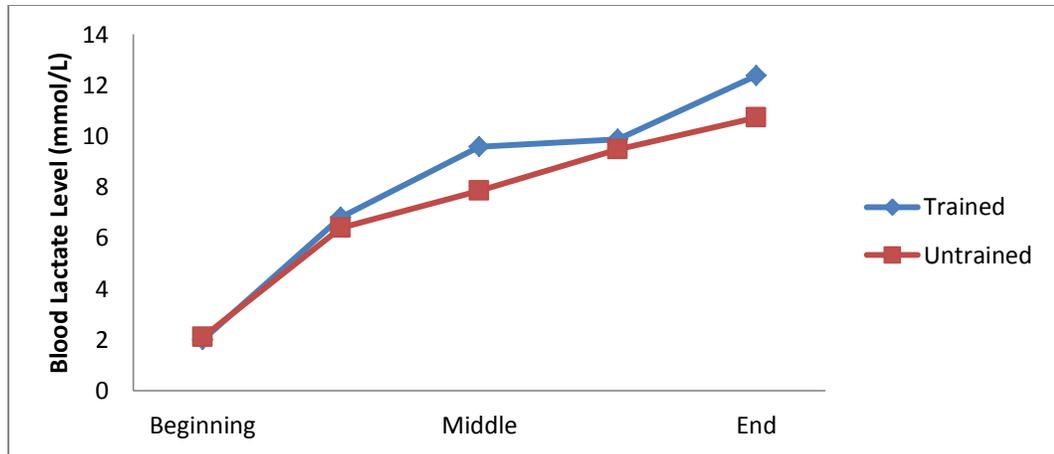


Figure 42 - Comparison of average BL between trained and untrained subjects in the BI pedal pattern;
 Bi: Bi-directional.

Duration

Duration of ride to voluntary exhaustion in all three pedal patterns were compared using the FO pedal pattern as a baseline time, since it is the “natural” pedal pattern.

On average, trained subjects were able to cycle for an average of (expressed in min:sec±SD) 20:47±12:53, 14:22±11:19, and 19:52±11:37 in FO, BO and BI pedal patterns respectively. Subjects in the trained group were able to ride in the FO pedal pattern longer than both the BO and the BI pedal pattern. Trained subjects were able to cycle 30.89% less time in the BO pedal pattern, and 4.44% less time in the BI pedal pattern as compared to FO pedal pattern. The differences in duration to fatigue for the trained group were not found to be significant ($p>0.05$).

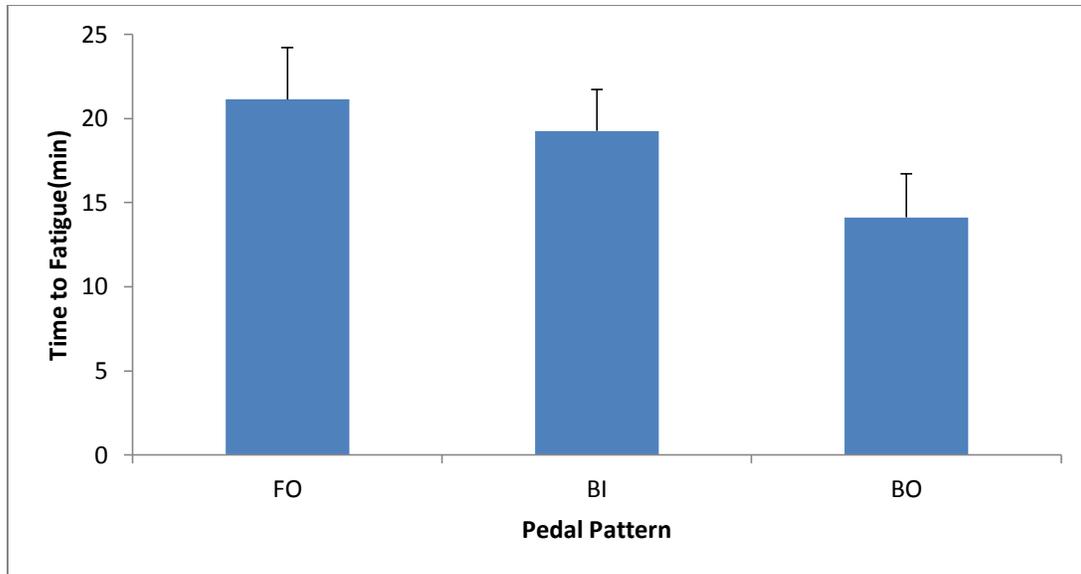


Figure 43 - Comparison of average time to fatigue for trained subjects in all three pedal patterns;

FO: Forward only; BO: Backward only; BI: Bi-directional.

Untrained subjects were able to cycle 10:26±3:14, 6:32±1:37, and 12:58±2:35 in the FO, BO and BI pedal patterns respectively. The untrained group exhibited different results. Compared to the FO pedal pattern, untrained subjects were able to pedal in the backward pedal pattern for 36.75% less time. This was highly significant ($p \leq 0.01$). Untrained subjects, however, were able to cycle in the BI pedal pattern significantly longer ($p \leq 0.05$) than the FO pedal pattern, with a 25.50% longer duration to fatigue than the FO pedal pattern.

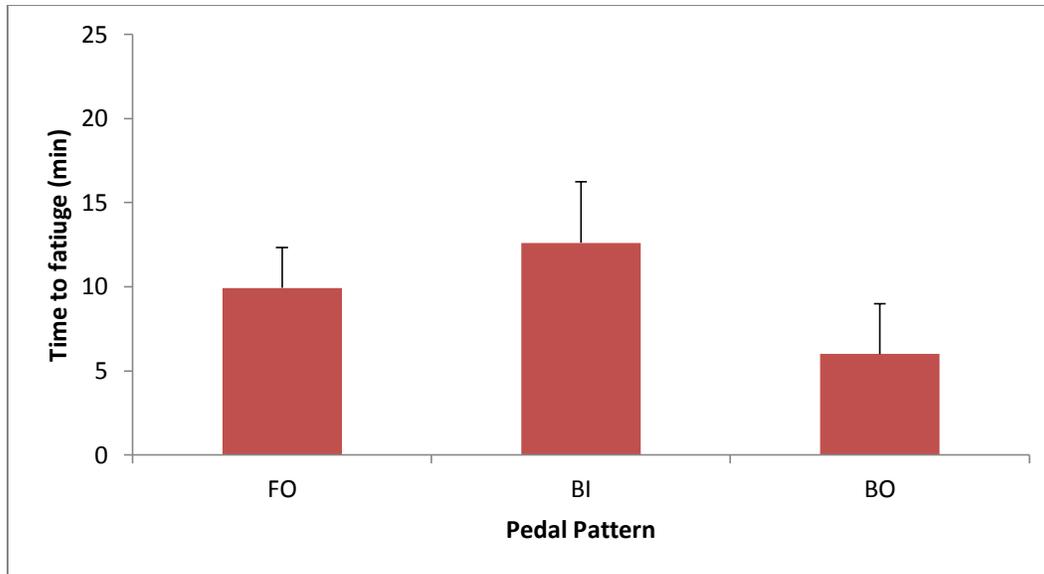


Figure 44 - Comparison of average time to fatigue for untrained subjects in all three pedal patterns;

FO: Forward only; BO: Backward only; BI: Bi-directional

To summarize, expressed as a percentage of the length compared to the FO pedal pattern, trained subjects were able to cycle 30.89% shorter duration and untrained subjects were able to cycle 36.75% shorter duration in the BO pedal pattern. Trained subjects were able to cycle 4.44% LESS time in the BI pedal pattern compared to the FO pedal pattern. However, untrained subjects were able to cycle 25.50% longer in BI pedal pattern as compared to the FO pedal pattern.

Subjects in the trained group, on average, were able to cycle longer in all pedal patterns as compared to the subjects in the untrained group, 101.2%, 119.8%, and 53.2% longer in FO, BO and BI pedal patterns respectively (see Figure 45). The difference between the two groups on the FO and BO pedal patterns were highly significant ($p \leq 0.01$), and the difference in the BI pedal pattern was significant ($p \leq 0.05$).

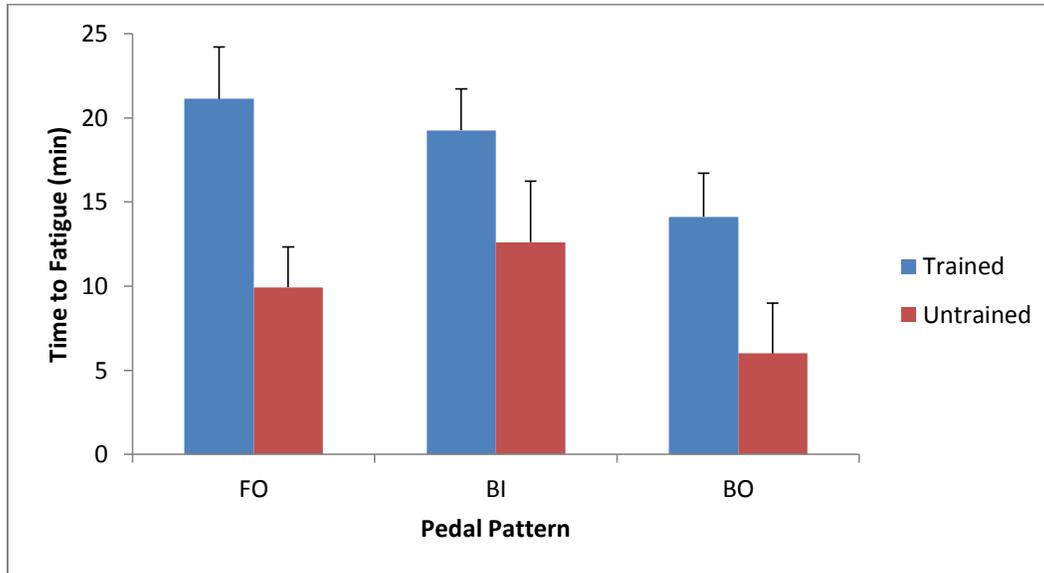


Figure 45 - Comparison of two groups: trained and untrained subjects' average time to fatigue in all three pedal patterns;

FO: Forward only; BO: Backward only; BI: Bi-directional

Chapter 5 – Discussion

The results from this study provide topics for discussion that can be divided into three different categories: 1) insights to the process of fatigue; 2) technique of trained in comparison with that of untrained groups; and 3) the effect of the bi-directional pedal pattern in comparison to the forward pedal pattern.

The process of fatigue

The results of this study give several points of discussion toward the process of fatigue. I will discuss four areas from my results that can monitor and provide feedback regarding fatigue in cycling. These areas include force pedals, joint kinematics, muscle activation levels, and physiological parameters. I will briefly discuss each of these below. An additional area that provides insight to fatigue is duration of cycling, or time to fatigue. I will discuss this in further detail in a later section of the discussion.

Force magnitude

Data resulting from force pedal measurements provided the magnitude of the force in three dimensions: medial/lateral, anterior/posterior, and vertical. The vertical forces (both push and pull forces) provided the most applicable feedback for the purposes of this study so I evaluated them in detail.

Results from the FO pedal pattern for trained subjects showed a clear pattern, significantly decreasing ($p \leq 0.05$) in both the push and pull forces as the trial progressed, the relative pull force decreasing more than the push force (15.88% compared to 22.45% in the push and pull force respectively). However, the magnitude of the pedal push force for the untrained subjects increased significantly ($p \leq 0.05$), while the increase of the

magnitude of the pull force was highly significant ($p \leq 0.01$). This phenomenon may be explained as follows: as the muscles in trained subjects fatigue, they are unable to put as much force into the pedal stroke in either the push or pull, while as muscles of untrained subjects fatigue, they focus more of their efforts on the push and start to use more of a pull in order to continue the pedal revolutions.

In the BO pedal pattern the magnitude of both the push and the pull force increased for trained subjects, although neither were significant. It is not surprising that the magnitude of the forces for the trained subjects responded similarly to those of the untrained subjects in the FO pedal pattern, since it is not a trained condition for either group. However, in the untrained group, the push force increased while the pull force decreased. Two explanations could account for this: undeveloped cycling technique in the untrained group, or by weak muscles required to pull while pedaling in the backward pedal pattern. The increase in forces at the end of the trial may result from an innate strategy that muscles use as they fatigue. In order to continue the pedaling when muscles start to fatigue the leg increases the amount of vertical force placed on the pedals, in either a push or a pull configuration. This theory is supported by the increase of force in both the push and pull for most of the conditions. This finding is consistent to findings by Bini (2008) where the force toward the end of the trial increased.

The magnitude of force for the untrained group in the BO pedal pattern showed an interesting pattern where, as the push force increases, the pull force decreases and vice versa (see Figure 9). This might suggest that there is a compensation strategy used by untrained subjects in this particular condition. When muscles are fatigued and unable to push, they compensate by pulling more on the pedal to complete the pedal revolution.

When they are too tired to pull, they rely more on the push to complete the pedal stroke. The FO condition for the untrained subjects showed a similar pattern (see Figure 7), but the pattern was not as defined in the FO condition. This might be because the forward pedal pattern is a familiar action, even for untrained subjects.

Force dispersion

At the beginning of the FO trial the location of the maximum push force for each revolution was concentrated in a small area, and at the end of the trial the location of the maximum push force is more spread out (see Figure 10, quad 1 and 2). We see a similar pattern with the pull force in this FO pedal pattern. We also see the same pattern of an increased dispersal of the maximum forces at the end of the trial in both the push and pull directions in the BO pedal pattern (comparing quad 3 and 4). This shows that as muscles fatigue the control pattern for the location of the maximum push or pull is affected. Bini (2010) found that joint moments increased as fatigue set in and explained it as an attempt to overcome decreased muscle contractions. This supports my findings with the dispersement of the maximum pedal force increasing as muscles fatigue.

Kinematics

In my discussion of kinematics I will specifically be referring to angles of lower limb joints. Looking at the joint angles for the knee, ankle in the horizontal direction, and ankle in the vertical direction we can see some common trends. In general, we can see that the ROM of the three joints follow a similar pattern at the beginning of the trial until just before the end (see Figures 22-29). At the end of the trials we see that, as the ROM for the knee decreases, the ROM of the ankle in both horizontal and vertical directions increase. This suggests that the ankle joint is compensating for less ROM in the knee

joint as muscles fatigue. This trend holds true for both trained and untrained subjects, and in both the push and pull on the pedal, but is most pronounced in the trained pull conditions for both the FO and BO pedal pattern. It is also clear that in both forward and backward pedaling among trained and untrained groups, the ankle joint responds similarly in terms of ROM for both horizontal (x) and vertical (y) directions. From this, we can generalize that, as muscles fatigue, the ROM of the ankle joint increases, compensating for the decreased ROM of the knee joint. Lattanzio et al. (1997) found that the knee and ankle joints changed as muscles fatigued. Results from Dingwell (2008) also support my findings. In their study they found that muscle fatigue does indeed alter kinematics. They reported that the greatest changes occurred in the trunk, hip and ankle. From my results we see that the knee also changed, but the changes were not as pronounced as those found in the ankle. The change in the ROM of the knee was comparable to that of the ankle in the horizontal direction, while the ROM of the ankle in the vertical direction was much smaller than both the ankle in the horizontal direction and the knee, although it fluctuated according to the ankle in the horizontal direction. My observations of changes in the hip, knee and ankle joint toward the end of the trial, and increased changes in kinematics of the ankle joint are consistent with findings by Bini (2008).

Chapman (2009) found that kinematics were not different between trained and untrained cyclists, which supports my findings for the knee and ankle joints. However, I saw significant differences ($p \leq 0.05$) in the hip joint between trained and untrained subjects (see Figures 30-33). I did find that the ROM of the hip did change in trained subjects, but the change in the ROM of the hip was greater in untrained subjects,

especially as fatigue set in. McEvoy (2008) reported that the pelvic angle has less variability in ROM in elite cyclists than in non-cyclists. As part of a kinetic chain, the pelvic angle will affect the hip angle. Since I did not measure the pelvic angle in this study, I can suggest that the hip angle will respond similarly to the pelvic angle, thus supporting my findings.

EMG

This finding in and of itself is important. The literature suggests that median value frequency is a good indicator of fatigue. However, results indicated that, for this study's dynamic trials, this was not the case.

One of the more applicable findings from my study included the results observed from the EMG data. When analyzing the median power frequency data, I did not observe any differences from the beginning to the end of the trials. This finding contradicts much of the research, which concludes that median power frequency is indeed a good indicator of fatigue (A, 1990; M, 1994; Soderberg & Knutson, 2000). I can conclude that median power frequency may be a good indicator of fatigue in static working patterns, but not in dynamic working patterns. Macdonald, Farina, and Marcora (2008) explained that in fatiguing exercise, learning effects could influence EMG results. This provides an explanation as to why the median power frequency data differs between static and dynamic exercise.

Activation levels of the muscles monitored decreased throughout the duration of the trial (expressed as a percentage of the initial activation level), until the end when they increased. This can be explained as a psychological "final effort" where, despite muscle

fatigue, subjects knowing it is the final push to the end are able to use the muscles at a greater intensity at the very end. I saw this phenomenon in each of the five muscles that I investigated; GM, BF, VM, VL, and TA (see Table 1). Dingwell (2008) reported that the muscles affected most by fatigue were the BF, GM, GL, and SOL, which agreed with my results. However, I found that GM and TA showed a greater decrease in activation levels suggesting that they were more affected by fatigue than the VL and VM. The BF did not have much change in activation levels, Dorel et al. (2009) also saw decreased activation levels in the GM and TA in their study, and they explained that the BF and gluteus maximus actually increase in activation levels in order to compensate for the decreased activity of the GM and TA. They also found smaller decreases in the VM and VL muscles. This identifies the GM and TA as main contributing muscles, where VM and VL are supporting muscles in the pedal stroke.

Physiology

Physiological parameters that were measured also provided relevant feedback regarding the fatigue process. As expected, heart rate increased significantly from resting heart rate to exercise heart rate, then slowly increased until subjects reached voluntary fatigue. I did not observe surprising results between trained and untrained subjects or between the three pedal patterns.

BL showed a similar trend as heart rate with a significant ($p \leq 0.01$) increase from rest to the start of exercise, then a gradual increase in levels until fatigue. However, trained subjects showed a couple of interesting results. One interesting result observed was that the end BL levels for the trained subjects in the BO condition were slightly lower than the end BL levels for the other two conditions, 14.74% lower than the levels

for the FO condition and 10.01% lower than the levels for the BI condition. Cyclists had a lower tolerance level for blood lactate when pedaling backwards, as they declared they were fatigued with BL levels being significantly lower than in the FO condition. This point leads to question if the trained subjects actually pushed themselves as hard in the BO condition as compared to the FO condition in a physiological sense. It is possible that the fatigue in the BO direction for this group was influenced by psychological factors. Since the BO condition is not a trained condition, it may be perceived as more difficult and cause cyclists to perceive their body as fatigued prematurely from a physiological standpoint. Perception of effort has been show to influence the central motor command (de Morree, Klein, & Marcora, 2012).

In the BO pedal pattern, the end BL were significantly lower ($p \leq 0.05$) than those in the FO pedal pattern. Two explanations exist; trained subjects had a lower tolerance for lactate build-up in the BO pedal pattern, or it is possible that subjects quit because of psychological fatigue as opposed to physiological fatigue, or fatigue due to perceived exertion. Toward the middle of the test, we can see that the average BL increased significantly ($p \leq 0.01$), then plateaued before a final increase at the end of the trial (see figure 38). Since in the BI condition, subjects were alternating between forward and backward pedaling, the plateau could be a result of the muscles' ability to clear some of the lactate build-up during the "rest period" of the alternate direction of pedaling. Eventually the lactate becomes more concentrated and continues to build up again, contributing to muscle fatigue. Although it was not significant, the end BL for the BI pedal pattern were lower than those in the FO pedal pattern. This point is consistent with

the theory of a psychological aspect to the perception of fatigue as discussed regarding the BO pedal pattern in trained subjects.

Technique / training effect

Chapman et al. (2008) found that the main difference between highly trained cyclists and untrained cyclists is that untrained cyclists have a greater variance. Muscle recruitment in untrained cyclists is less refined than in trained cyclists, likely resulting from a trained effect. This is certainly supported by my findings, and can explain the differences seen between trained and untrained subjects in the ROM of the maximum push and pull forces (see Figures 13 and 16). Untrained subjects have significantly higher ($p \leq 0.05$) ROM for the push forces than trained subjects in the FO pedal pattern (see Figure 13). Not only is the ROM higher in untrained subjects, but it does not follow any general pattern. This shows a lack of motor control in untrained subjects. However, the pull force does not show any significant differences between trained and untrained subjects. Also, referring to Figure 10 we can see that at the beginning of the trials the pull force is more spread out than the push force (see quad 1). This dispersion of forces shows that the pull force is not as refined as the push force. These results suggest that trained subjects may not have a refined technique and the sporadic nature of the graph also suggests a lack of motor control in the pull portion of the cycle. Perhaps I would have seen different results from professional or elite cyclists.

In trained subjects comparing the forward and backward pedal pattern showed opposing effects on the ROM of the push forces (see Figure. 18), but the same effects on the ROM of the pull forces (see Figure 19). Untrained subjects saw the opposite to be true, with similar effects on the push force between FO and BO pedal patterns (see Figure

20), and opposing effects on the pull force between the FO and BO pedal patterns (see Figure 21). For both the push and the pull forces we see that the FO pedal pattern has a smaller ROM than the BO pedal pattern, which is to be expected since the FO pedal pattern is familiar. We would expect to see a greater range in the BO pedal pattern since it is an unfamiliar motion. We also see an interesting pattern happening in the comparison of FO and BO pedal patterns for the trained subjects in both the push and the pull. In the BO pedal pattern, the ROM of the push force gradually decreases until a sudden increase at the end of the trial. The BO pedal pattern being unfamiliar, they may be learning and adapting their technique as the trial progresses (MacDonald, 2008). The increased ROM at the end of the trial likely resulted from muscle fatigue. The ROM for the FO pedal pattern in trained subjects gradually increased from the beginning to the end of the trial. This supports the theory of ROM increasing as muscles become fatigued.

When comparing forward pedaling to backward pedaling, we can see that both the push and pull forces are widely dispersed in backward pedaling (see Figure 10 quad 1 compared with quad 3). This shows less refined motor control pedaling in the backward direction, most likely because it is a new skill and subjects have not had an opportunity to train in that area. It is likely that, with some training, the location of the forces in the backward pedaling pattern may be more concentrated in the same location. We may even see a similar dispersement as seen in forward pedaling. We can see from Figures 14 and 15 that in the backward direction, the range of the location for the maximum force does not follow a gradual pattern for either trained or untrained subjects in the BO pedal pattern. The ROM in the BO pedal pattern was similar for both trained and untrained subjects (see Figure 16). This is not a surprising result since neither trained nor untrained

subjects are experienced in backward pedaling. Both groups show a lack of motor control when pedaling backwards. Training in backward pedaling may reduce, or even eliminate this difference. Based on the findings above, I can conclude that force pedals can give us insight into pedaling technique.

The data from the force pedals coincides with observations in the joint angle data as well. I saw some interesting results when comparing the ROM of joint angles between FO and BO pedal patterns (see Figures 34-35). The increases and decreases in ROM for each of the joints seemed to follow an opposite pattern, suggesting a phase shift of not only muscle recruitment (Neptune & Kautz, 2000; Raasch, 1997; C. Raasch & Zajaz, 1999; Ting et al., 1999), but a phase shift in joint responses, possibly as a result of the phase shift of muscle activations. The results from Chapman et al. (2008) can be extended in the joint angles to explain the differences I saw between trained and untrained subjects in the ROM of the hip, knee, and ankle joints when the maximum push and pull forces occurred. Untrained subjects have significantly higher ($p \leq 0.05$) ROM for both the push and pull forces (in some places differences are highly significant ($p \leq 0.01$)) than trained subjects in the FO pedal pattern (see Figures 11 and 12). However, the joint angles observed in the BO pedal pattern do not show that either trained or untrained subjects had better motor control, or better technique than the other group (see Figures 16 and 17). The ROM in the BO pedal pattern for both trained and untrained groups show clearly that this is an untrained pedal pattern for both groups and that there is a lack of motor control when pedaling in the backward direction. Since backward pedaling is not a trained condition, and there is strong evidence suggesting that there is a lack of motor control when pedaling backwards, cyclists would not be at their maximum efficiency

when pedaling in the backward direction. It would be interesting to explore backward pedaling after subjects have had a chance to train in the backward direction to see if these motor control patterns improve.

Bi-directional influences

Time

The most relevant result observed relating to the purpose of this study was the time to voluntary fatigue in the three different pedal patterns. Trained subjects showed no significant differences in their times to fatigue. However, untrained subjects were able to cycle significantly ($p \leq 0.05$) less time in the BO pedal pattern, but significantly ($p \leq 0.05$) longer in the BI pedal pattern, as compared to the FO pedal pattern (see Figure 44). This result suggests that pedaling in the BO pedal pattern is not very efficient. Despite the inefficiency of backward pedaling, there was a delayed onset of fatigue for untrained subjects in the BI pedal pattern, allowing them to cycle 25.50% longer in the BI pedal pattern as compared to the FO pedal pattern. BL in the BI pedal pattern for the untrained group were not significantly different ($p > 0.05$) than those found in the other two pedal patterns, suggesting that they truly did cycle to physiological fatigue in the BI condition.

Results for trained subjects differed from the results observed with the untrained group. Time to voluntary fatigue in the trained group in the BI pedal pattern was 4.44% less than the time to voluntary fatigue in the FO pedal pattern (see Figure 43). The results in the BI pedal pattern could be attributed to a psychological explanation for fatigue. Marcora (2010) suggested that exercise tolerance in highly motivated subjects is limited by their perception of effort. In other words, if a subject perceives that a task is more

difficult, they tend to reach a state of fatigue more quickly. Trained subjects perceived the BO pedal pattern to be more difficult. It appears that pedaling in the BO direction for trained subjects hindered their performance. In the BI condition, subjects were required to pedal backwards for short periods through the trial, and their fatigue may have reflected their perceived exertion. Although the time to fatigue in the BI pedal pattern for the trained group was not significantly different compared to that of the FO pedal pattern, the results indicated that trained subjects had significantly lower BL levels in the BI condition. This suggests that they may not have actually cycled to the same physiological state of fatigue in the BI pedal pattern as they did in the FO pedal pattern. Had they continued cycling to the same physiological state of fatigue as they had in the FO pedal pattern, their time to fatigue in the BI pedal pattern might have been significantly longer than that of the FO pedal pattern.

Limitations and delimitations

Limitations

There were a few limitations in this study, most of them related to the equipment used. The trainer where the bicycle was mounted on in the lab did have the capability of adjusting resistance levels in order to attain a desired power output level. However, it could only be adjusted in ten-Watt increments. This meant that I was limited to setting the resistance level for subjects to the nearest ten-Watt value, differenced ranging from four Watts lower to five Watts higher than the calculated resistance levels for both forward and backward pedaling. Another limitation was the bicycle frame itself. The prototype was built on one bicycle, meaning I had only one size of frame to use. In order to overcome this limitation I fit the bicycle to subjects as best as I could by making minor

adjustments to the seat height and tilt, stem length, and handle bar placement. Despite these adjustments I was able to make, I had to screen subjects based on their height as well. Because I was measuring forces exerted on the pedals I had special force pedals attached to the bike. This resulted in the inability for subjects to use pedal that had toe clips. To try to compensate for the lack of toe clips I had toe straps to strap the foot to the pedal; but these were not as effective as toe clips. This may have affected the technique of some of the cyclists as they were not able to pull as forcefully as they normally would when cycling. In this study surface EMG was used to monitor muscle activation levels. This limited the muscles under investigation to surface muscles. I was not able to monitor the activation levels of muscles such as the soleus and the gluteal muscles, which are some of the main contributing muscles in cycling. A final limitation that I will mention here is the ratio used for the BI pedal pattern. This study did not investigate what the optimal ratio of forward to backward pedaling would be for pedaling in the BI pedal pattern. I chose a ratio based on an empirical method as previously described.

Delimitations

Delimitations of this study include the target population. There were two target populations used in this study; trained cyclists (including triathletes) and untrained individuals. The untrained group consisted of people who may have been active, but did not regularly train for any sport. Trained cyclists were defined as cyclists who had at least two years of cycling experience and trained a minimum of five hours a week at the time of the study. Another delimitation of this study was the cadence of the rider. I asked the riders to maintain a cadence between 70 rpm and 110 rpm. As soon as riders were unable

to maintain a cadence above 70 rpm I stopped the trial, otherwise the trial was stopped when the subject themselves determined that they were unable to continue due to fatigue.

Chapter 6 - Conclusion

From the results of this study I can conclude four major things. First, kinetic (force pedal) and kinematic (joint angle) data are good indicators of fatigue. Second, kinetic and kinematic data are able to provide insight to cycling technique and an understanding of muscle control patterns. Third, while median value frequency values obtained from EMG data may be an indicator of fatigue in static exercise, they are not a good indicator of fatigue in dynamic exercise. Fourth, pedaling in a BI pedal pattern appears to delay the onset of fatigue in untrained subjects.

Recommendations for future work

The main purpose of this study was to investigate the efficiency of a BI pedal pattern, and results have shown that the BI pedal pattern did delay the onset of fatigue for untrained subjects. Considering the results from this study there appears to be a negative influence of a training effect on trained subjects in the BI pedal pattern. It would be of great importance to conduct another study similar to this one with trained cyclists pedaling to voluntary fatigue after they have had an opportunity to train in backward pedaling so that they are accustomed to the motion. This would eliminate the training effect, and any negative influences of muscle memory for the trained group.

A second area that needs to be explored is the BI pedaling itself. An investigation on finding the optimal forward to backward ratio would be necessary to determine if the BI pedal pattern really is more efficient than the traditional FO pedal pattern. Subjects should have plenty of practice pedaling in the backward direction prior to an investigation of an optimal ratio to ensure that the backward pedal direction is a familiar motion.

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APPENDICES

A. Subject consent forms

Letter of Information and Informed Consent

Name: _____

Last

first

middle initial

Address: _____

Phone Number: _____ (Home) E-mail: _____

_____ (Mobile)

_____ (Work)

You are invited to participate in a research study investigating the efficiency of a new bicycle design; a bi-directional pedaling bike. The purposes of this study are to test if this new bicycle design is both physiologically and biomechanically more efficient than the traditional forward only pedaling bicycle design.

This study will require you to come into the lab for four sessions on four different days. Each session will take approximately 70 minutes for a total time commitment of 240 minutes. This will allow for 10 minutes to get set up, and warmed up prior to the testing session. The first day of testing we will be conducting a maximum power output test in

order to provide us with baseline data to work with on the sessions to follow. The first session will also be used as a familiarization session for the backward pedaling motion. Each consecutive testing day will consist of one of three different methods of pedaling the bicycle; forward, backward, and bi-directional. These will be clearly explained to you at the beginning of each session. The order of these sessions will be randomly selected.

Each test day will start with a collection of blood lactate levels. This collection will be repeated in ten minute intervals. You will be asked to pedal in the instructed pedaling pattern for as long as you feel you are able, up to a maximum of 60 minutes. If at any stage in the trial you feel you are not able to continue the trial, please inform the investigator. The trial will be terminated immediately.

It should be noted that there may be some slight discomfort when we conduct the blood lactate test as it requires a finger prick with a sterile lancet in order to obtain a small drop of blood. We will be sure to clean and disinfect the finger prior to the prick, and we will ensure that the conditions are completely sterile. This discomfort will only be momentary and there should be no lasting effects. There is a slight risk of infection due to the finger prick but this will be minimized by using completely sterile conditions.

The bicycle seat and handlebars will also be sterilized between users to help us to maintain a sterile environment. We will also be wiping down the frame after each use.

All information obtained for the purposes of this study will be kept confidential and will not be released without your permission. All research assistants will be signing a confidentiality agreement in order to maintain your privacy, and we will be assigning a unique code to each participant to use for further identification. Your name or other information will not be used in connection with the data collection. Your personal information will only be available to the investigator directly involved with this project and her supervisor.

We will be taking a digital video recording to help us synchronize all of the data readings in the collection process. We will only use this recording for educational purposes, and only if you give us permission. In the event that this digital recording is used for educational purposes, we will mask your identity in order to maintain your anonymity. If you would be willing to grant us permission to use this digital recording for educational purposes only, please indicate below by placing your initials next to the appropriate response:

There is no direct benefit to you for your participation in this study. If you wish to receive the results from the study, you can request your personal and/or a copy of the aggregate results of this study to be sent to you at the completion of the study. Please e-mail the researcher or the co-investigator (please see e-mail addresses below) with your request.

Data collected will be used as part of a thesis and will be submitted for publication in a journal. The results of this study may also be presented at an academic conference in the future.

Your participation in this study is voluntary. If at any stage you choose to withdraw yourself from the study for whatever reason, please inform the investigator. Be assured that the decision to withdraw will not affect your relationship with the University of Lethbridge or the Department of Kinesiology and Physical Education in the future.

If you have any questions about the research at any time please do not hesitate to ask. You can contact Sarah Crowe (sarah.crowe@uleth.ca, (403)332-4037 - Primary investigator) or Dr. Gongbing Shan, Ph.D., Professor, Department of Kinesiology and Physical Education, University of Lethbridge (g.shan@uleth.ca, (403)329-2683. Please inform the investigator if you would like a copy of this letter to keep for your records. Questions regarding your rights as a participant in this research may be addressed to the Office of Research Services, University of Lethbridge (Phone: 403-329-2747 or Email: research.services@uleth.ca).

We appreciate your interest in participating in this research project.

Consent:

In signing this I agree that:

- I am in good health and there is no reason that I should not be able to participate in this study for medical reasons.
- I have read and understand the procedures of this study and the expectations of myself as a subject.
- All of my questions have been answered to my satisfaction.
- I am a willing participant in this study.
- I recognize that I have volunteered for this and I understand that I can withdraw at any stage of the testing if I so choose.
- I understand that I will not be compensated for my participation in this study.

Print Name

Signature of Participant

Date

Signature of Investigator

Informed Consent

Biomechanical Evaluation of an Innovative Bi-direction-Pedaling Bicycle

Bicycle Project

*Biomechanics Laboratory
University of Lethbridge*

We invite you to participate in a study that aims to reduce soft tissue injuries (vocational or recreational). Such injuries affect a significant portion of Canada's population, creating both health and social problems. Due to our lack of understanding of biomechanics, much of the professional equipment designed for biological enhancement of repetitive physical capabilities leaves much to be desired. This project will explore how external loading on the limbs during a variety of repetitive physical activities translates to internal load levels in major joints and muscles of these extremities. The information obtained will guide future design and engineering of equipment meant to increase human performance efficiency and to reduce physical injuries such as Overuse Syndrome. A reduced rate of soft tissue injuries will definitely benefit people involved as well as our health and social system. This study focuses on revealing the effect of alternative equipment design on internal load. To answer this question, the project examines here bicycling, a common equipment dependent, repetitive movement. Based on previous research, changing the direction of pedaling to backward pedaling varies loading patterns and loading conditions for the lower extremities; thus it is possible that a combination of forward and backward pedaling could prove beneficial for repetitive injury reduction. To test this hypothesis, the PI has designed a *forward-and-backward-pedaling-power-generation* bicycle for use in this test. The equipment generates forward-power for the bike irrespective of the subject's pedaling direction. The study will compare the internal load of three pedaling patterns: forward, backward and forward-backward.

The experiment takes about 60 minutes. You will be asked to wear a black garment made of stretchable material, which covers the upper and lower body. Affixed to the garment will be 42 reflective markers, each with a diameter of 9mm. Before the test, you will be allowed to perform a sufficient number of warm-up exercises to get used to the test environment. After warm-up you will be asked to perform the three type pedalings at low or high cycling speed. During each pedaling, the kinematic (3D motion), kinetic (pedaling force) and muscle activity (EMG) data will be collected simultaneously. For collecting EMG, we will put electrodes on your skin of both legs. These read the electrical activity in the selected leg muscles. The electrodes require good contact with the skin. In some cases, this may require the shaving of hair in a small area (2 cm × 2 cm) to ensure clear signals. The shaving will be done using disposable razors to ensure: one subject one razor. The tests are natural and do not use any sort of medication. They are much like your performance and/or practice; therefore, there should be no risk for you during the test. The information gathered from you during this study is considered confidential. To maximize your confidentiality, you will be assigned a code, and this code will be used instead of your name at all times. All personal information (body weight, body height, age, years of training and practice hours per

week) can only be accessed by researchers involved in this study and will not be disclosed without your permission. We may, however, wish to use your data measurements for a research presentation or education purposes in the future. Your identity will be kept confidential. It should be mentioned that the 3D motion capture system will not in any way videotape the subject's faces, so that subjects truly do remain anonymous.

Your participation in this study is entirely voluntary and you may withdraw from participating at any time. Should you decide not to participate in this study, your relationship with the Biomechanics Lab or any other department of the University of Lethbridge will not be affected in any way. If you wish to see your performance analysis, we will supply you a CD containing your 3D dynamic analysis data. For any further questions about this research, please feel free to contact Dr. Gongbing Shan, at (403) 329-2683. If you have any further questions regarding your rights as a participant please contact the University of Lethbridge Office of Research Services at (403) 329-2747.

Your signature below indicates that you have read and understood the information provided above, and that any and all questions you might ask have been answered to your satisfaction. Your signature also indicates that you willingly agree to participate in this study, and that you understand you may withdraw from this experiment at any time.

I have read the attached Informed Consent form and I consent to participate in the “Biomechanical Evaluation of an Innovative Bi-direction-Pedaling Bicycle” research study.

Printed Name: _____ Date: _____

Signature: _____

Witnessed by: _____ Date: _____

B. Par-Q questionnaire

Physical Activity Readiness
Questionnaire - PAR-Q
(revised 2002)

PAR-Q & YOU

(A Questionnaire for People Aged 15 to 69)

Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions in the box below. If you are between the ages of 15 and 69, the PAR-Q will tell you if you should check with your doctor before you start. If you are over 69 years of age, and you are not used to being very active, check with your doctor.

Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly: check YES or NO.

YES	NO	
<input type="checkbox"/>	<input type="checkbox"/>	1. Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?
<input type="checkbox"/>	<input type="checkbox"/>	2. Do you feel pain in your chest when you do physical activity?
<input type="checkbox"/>	<input type="checkbox"/>	3. In the past month, have you had chest pain when you were not doing physical activity?
<input type="checkbox"/>	<input type="checkbox"/>	4. Do you lose your balance because of dizziness or do you ever lose consciousness?
<input type="checkbox"/>	<input type="checkbox"/>	5. Do you have a bone or joint problem (for example, back, knee or hip) that could be made worse by a change in your physical activity?
<input type="checkbox"/>	<input type="checkbox"/>	6. Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?
<input type="checkbox"/>	<input type="checkbox"/>	7. Do you know of any other reason why you should not do physical activity?

**If
you
answered**

YES to one or more questions

Talk with your doctor by phone or in person BEFORE you start becoming much more physically active or BEFORE you have a fitness appraisal. Tell your doctor about the PAR-Q and which questions you answered YES.

- You may be able to do any activity you want — as long as you start slowly and build up gradually. Or, you may need to restrict your activities to those which are safe for you. Talk with your doctor about the kinds of activities you wish to participate in and follow his/her advice.
- Find out which community programs are safe and helpful for you.

NO to all questions

If you answered NO honestly to all PAR-Q questions, you can be reasonably sure that you can:

- start becoming much more physically active — begin slowly and build up gradually. This is the safest and easiest way to go.
- take part in a fitness appraisal — this is an excellent way to determine your basic fitness so that you can plan the best way for you to live actively. It is also highly recommended that you have your blood pressure evaluated. If your reading is over 144/94, talk with your doctor before you start becoming much more physically active.

DELAY BECOMING MUCH MORE ACTIVE:

- if you are not feeling well because of a temporary illness such as a cold or a fever — wait until you feel better; or
- if you are or may be pregnant — talk to your doctor before you start becoming more active.

PLEASE NOTE: If your health changes so that you then answer YES to any of the above questions, tell your fitness or health professional. Ask whether you should change your physical activity plan.

Informed Use of the PAR-Q: The Canadian Society for Exercise Physiology, Health Canada, and their agents assume no liability for persons who undertake physical activity, and if in doubt after completing this questionnaire, consult your doctor prior to physical activity.

No changes permitted. You are encouraged to photocopy the PAR-Q but only if you use the entire form.

NOTE: If the PAR-Q is being given to a person before he or she participates in a physical activity program or a fitness appraisal, this section may be used for legal or administrative purposes.

"I have read, understood and completed this questionnaire. Any questions I had were answered to my full satisfaction."

NAME _____

SIGNATURE _____

DATE _____

SIGNATURE OF PARENT
or GUARDIAN (for participants under the age of majority) _____

WITNESS _____

Note: This physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if your condition changes so that you would answer YES to any of the seven questions.



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