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Literature review

Muscle recruitment pattern in cycling: a review

Raymond C.H. So[a,b], Joseph K.-F. Ng[b,*], Gabriel Y.F. Ng[b]

[a]Sports Science Department, Hong Kong Sports Institute, Sha Tin, Hong Kong, China
[b]Department of Rehabilitation Sciences, The Hong Kong Polytechnic University, Hung Hom, Hong Kong, China

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Abstract

Studies have indicated that the muscles work in a systematic and coordinated way to generate and direct power from the human body to the crank during cycling. Understanding of the muscle involvement or recruitment pattern during cycling will be useful for developing specific and effective muscle training and rehabilitation programs for cyclists. Moreover, it will also facilitate the use of the cycling ergometer for therapeutic purpose. This paper reviews the current literature on muscle recruitment pattern during cycling and the effects of muscle fatigue, cadence, riding posture and seat height on this recruitment pattern. In the power phase or 'downstroke', the hip, knee and ankle joints extend simultaneously for the pushing action, whilst in the recovery phase or 'upstroke', they flex together to pull the pedal back to the top dead center of the crank cycle. Recent studies have indicated that in this repeated sequence, the mono-articular muscles are mainly involved in the generation of positive work whereas the biarticular muscles are responsible for regulating force transmission. Some muscles co-activate during cycling to provide synergistic actions and other functional needs.

Muscle fatigue is an important factor affecting cycling performance. It has been reported that muscle fatigue in the lower body would alter the cycling motion and muscle activation pattern. Therefore, studying the change of muscle activation pattern during cycling at the fatigued level may shed light on the sequel of local muscle fatigue. A muscle training program specifically for cycling can then be designed accordingly. Additionally, the change of cadence during cycling will affect the muscle recruitment pattern. There is a unique cadence that minimizes the muscle activation level at a specific level of power output. This cadence will increase as the power output increases. The change of riding posture from sitting to standing renders the pelvis unsupported and the body weight will assist the power phase of pedalling. Similarly, changes to the seat height will alter the posture which will affect the directions of muscle actions to the crank, thus changing the muscle recruitment pattern.

Keywords: Cycling; Muscle recruitment; Fatigue; Review

1. Introduction

Cycling is a one of the most popular sports in the world. Cyclists may race, tour or simply exercise to keep fit. As more people become involved in cycling, the incidence of its associated injuries has increased. Cycling is non-weight bearing and the action is smooth and non-paring, making injuries less likely. However, due to considerably longer periods spent in training and racing compared to many other sports, there are patterns of overuse injury unique to cycling (MacAuley, 1995). Wilber, Holland, Madison, and Loy (1995) reported that among all the recreational cyclists who responded to their questionnaire, 85% reported one or more overuse injuries, with 30% requiring medical treatment. The most common sites for overuse injury were the neck (48.8%) followed by the knee (41.7%). Holmes, Pruitt, and Whalen (1994) stated that knee pain is the most common lower extremity overuse problem in cyclists which, ironically, is caused by strong knee extensors. If only the knee extensors are strengthened, the patella will be over-strained because most of the energy in the power phase is transmitted through the patella (Sanner & O'Halloran, 2000). This problem can result in decreased performance, participation and enjoyment for cyclists at all levels.

The knee extensor muscle group is the prime mover to generate energy to the crank in the downstroke phase of cycling (Raasch, Zajac, Ma, & Levine, 1997) and many serious cyclists emphasize their muscle training on the knee

* Corresponding author. Tel.: +852 2766 6765; fax: +852 2330 8656.
E-mail address: rsjoseph@polyu.edu.hk (J.K.-F. Ng).

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extensor muscles for performance enhancement. However, this may increase their risk of getting knee injuries. Therefore, an understanding of the muscle involvement or recruitment pattern during cycling is essential for developing a specific and effective muscle training program for cyclists for performance enhancement and injury prevention. Moreover, it also helps sport physiotherapists to determine which muscles need specific training to recondition elite cyclists after injury.

Cycling has been recognized as a recreational and sporting activity that has many therapeutic qualities. Fleming et al. (1998) suggested that stationary cycling at the appropriate cadence and resistance is an effective rehabilitation exercise for patients with anterior cruciate ligament injury to increase muscle activity without subjecting the ligament to undue strain. With an understanding of the normal muscle recruitment pattern of this exercise, sports physiotherapists can focus on a particular phase of the cycling action to train a particular muscle group.

Even though cycling is generally regarded as a closed-kinetic chain exercise, the joint position and loading in the kinetic chain may not always be predicted at a particular sequence. de Groot et al. (1994) indicated that muscular work depends on the length–tension, force–velocity power relationships of the involved muscles. The effectiveness of force production is affected by joint angles, muscle lengths and muscle moment arms. These variables in turn are altered by changes in the rate of pedaling, position and orientation of the body and changes in seat height. In addition to this, Asplund and St Pierre (2004) stated that muscle fatigue during cycling might induce alternations in pedaling technique leading to stress and symptoms in other parts of the kinetic chain. Therefore, knowledge of the muscle fatigue pattern in the major muscles during cycling will not just enable a better prescription of muscle training programs, it may also reduce the risk of overuse injury. This article provides a review for clinicians to appreciate the complexity of cycling so that they can modify the exercise to achieve the purpose of training on a particular muscle or range that they aim for.

2. Classical view on muscle recruitment during cycling

Schmidt (1994), an experienced scientific cycling coach, stated that the most important muscle for cycling is the quadriceps, whilst pulling on the pedals depends on the hip flexors. The lower leg muscles power the pedaling motion with the calf muscles being active during the entire pedal revolution and the muscles of the anterior tibial compartment are only responsible for fixing the foot in place whilst pulling back on the pedals. Schmidt (1994) also stressed the importance of the smooth pedal stroke for the bicycle racer, which refers to the even distribution of power to the pedals during the course of the entire pedal revolution. The use of racing pedals that restrain the foot on the pedal enable power transmission from top to bottom during pushing, pressing and pulling. This enables the road racers to use all the leg and hip muscles during the entire crank revolution cycle.

Muscles in the trunk and arms provide a counter-balancing force to the lower limbs during the pedaling motion. The hand, arm, shoulder, abdomen and back form a muscular sling, which rhythmically moves back and forth in supporting the trunk and pelvis (Schmidt, 1994). The ipsilateral arm and other structures provide the support to counteract the leg extension force. Nearly all the major skeletal muscle groups are utilized. A general description of the function of the major muscle groups during cycling has been developed but no detailed description of the level of force and working time/phase of each muscle group with respect to the pedal cycle is available.

3. Muscle recruitment during cycling based on electromyopraphic (EMG) pattern

Before discussing the muscle recruitment in cycling, a brief description of the crank cycle is essential. The crank cycle can be broken down into three phases (Fig. 1):

1. The propulsive/power/downstroke phase.
2. The pulling/recovery/upstroke phase.
3. The pushing phase, in which the foot is pushed forward at the top dead center (TDC).

Gregor and Rugg (1986) studied the activity pattern of eight muscles by electromyographic monitoring in the leg whilst cycling at 85 rpm against a moderate load in 10 competitive male cyclists riding at their own personal comfort level. Six muscles (vastus medialis, vastus lateralis, rectus femoris, tibialis anterior, biceps femoris and gluteus maximus) had more than 50% of their respective maximum

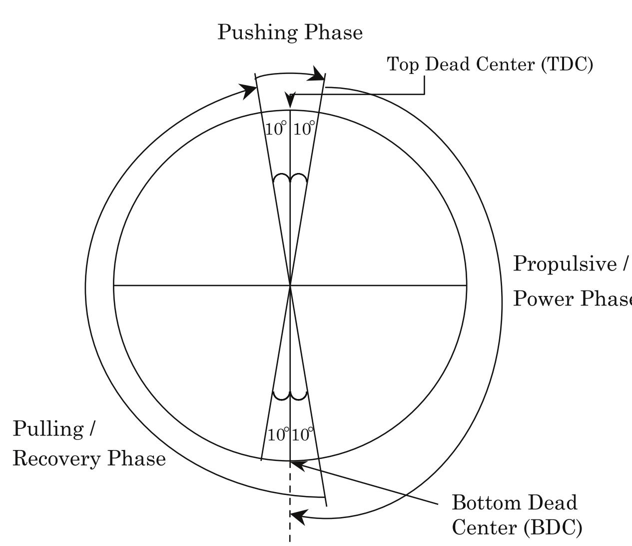

Fig. 1. The three phases of the crank cycle during the cycling action.

activity during the first half of propulsion (0° TDC to 90°). The quadriceps (knee extensors) became less active, whilst the hamstrings, gastrocnemius and gluteus maximus maintained their activities until the bottom dead center (BDC) in order to complete the propulsive phase. This would lead to significant hip and knee extension and ankle plantar flexion in the propulsion phase. In a later report, Pruitt (1988) also described a similar muscle activation pattern.

In a more recent study, Gregor and Conconi (2000) presented the muscle recruitment pattern during cycling, with more detailed description of the muscle activity, especially during the recovery phase. Both medial and lateral vasti muscles, being single-joint knee extensors, exhibited a rapid onset and cessation with relatively constant activity in-between during the downstroke phase. Conversely, the rectus femoris, which is a hip flexor and knee extensor, demonstrated a more gradual rise and decline. The soleus, being a single-joint ankle plantar flexor, was recruited just before the gastrocnemius. The semimembranosus and semitendinosus were recruited after TDC and their peak activities occurred at, or slightly after, 90° from TDC. Peak activity in the semitendinosus occurred slightly after that of the semimembranosus, whereas biceps femoris was the most variable among the hamstring muscles. The authors stated that during the recovery phase, from 180 to 360°, the lower extremity flexed actively and that this served two functions: firstly, it reduced the resistance on the crank to the propulsive phase on the contralateral limb; and secondly, it provided enough flexion to rotate the crank and assisted the contralateral limb in propulsion. A summary of the muscle activity pattern is described in Table 1.

From the above descriptions, an optimal pedaling technique could provide effective force on the pedals during both the propulsive and recovery phases. The hip and knee flexors work to drive the pedal rearward near the bottom dead center and to lift the pedal during a large portion of recovery (Broker & Gregor, 1996).

The importance of the upper extremity and trunk muscles in cycling was stressed by Gregor and Conconi (2000) but no detailed description was stated. There has been no scientific study done to evaluate the upper body and trunk muscle activity pattern during cycling. Only the coach manual has illustrated the upper body muscle work in cycling (Schmidt, 1994). There is a need to evaluate the extent of upper body and trunk muscle activity level during cycling in order to guide the optimal strength-training program for the cyclists.

4. Muscle recruitment during cycling based on biomechanical modelling

Because the relationship between EMG and force is uncertain during non-isometric cyclic contractions, the precise muscle coordination in the delivery of energy to the crank cannot be clearly described. Also, some potentially important muscles, which are situated deep inside the body, are difficult to study with surface EMG. Therefore, studying how energy transfer happens from the body to the bike is a means to better understand the muscle activation pattern.

Raasch et al. (1997) reported that based on a simulation study, the net hip extension torque primarily delivered energy to the limb segment, which was then transferred to the crank by net ankle torque. Furthermore, Raasch and Zajac (1999) suggested a model utilizing three pairs of alternating muscle groups in excitation to describe the function of each muscle group in the torque transference. The uniarticular hip extensors—gluteus maximus and knee extensors—vastus lateralis and medialis (i.e. the extensor group, or E group) co-excited during cycling and worked alternately with the uniarticular hip flexors—iliacus and psoas and the knee flexor—short head of biceps femoris (i.e. the flexor group, or F group). These formed the E–F pair. A second pair consisted of the biarticular rectus femoris (RF) and tibialis anterior (TA), which alternated with the posterior thigh muscles—medial hamstrings and long head of biceps femoris (HAM) and ankle plantar flexors including the soleus and gastrocnemius (SG), forming the final pair. The E/F groups produced energy to propel the crank whilst the RF/TA and HAM/SG groups acted as rigid links to facilitate the energy transfer. The RF/TA pair provided energy to propel the crank toward the end of flexion and during the flexion-to-extension transition; whereas the HAM/SG pair were active near the end of

Table 1
Average patterns of muscle activation during the pedaling cycles for the major muscle groups (adapted from Ryan & Gregor, 1992)

Muscles	Function	Approximate range of action (°)	Approximate peak activity angle (°)
Gluteus maximus	Hip extension	340–130	80
Vastus lateralis	Knee extension	300–130	30
Vastus medialis	Knee extension	300–130	30
Rectus femoris	Knee extension/Hip flexion	200–110	20
Soleus	Ankle stabilizer	340–270	90
Gastrocnemius	Ankle stabilizer/Knee flexion	350–270	110
Tibialis anterior	Ankle stabilizer/Ankle flexion	All the range	280
Hamstrings (without biceps femoris)	Knee flexion	10–230	100
Biceps femoris	Knee flexion/Hip extension	350–230	110

extension and during the extension-to-flexion transition (Zajac & Gordon, 1989; Raasch et al., 1997). In this pattern of activity, Raasch and Zajac (1999) stressed that the ankle must be stabilized to ensure complete transfer of the extension energy to the crank. Raasch et al. (1997) highlighted that if the plantar flexors did not co-excite during downstroke, energy from extensors would go towards accelerating the limbs by dorsiflexing the ankle and hyperextending the knee rather than the crank.

For the ankle movement, Raasch and Zajac (1999) stated that the ankle could employ different strategies or pedaling movements during cycling. First, the ankle could have more motion before the pedal passed through the BDC by dorsiflexion to store the kinetic energy and then plantar flexion just before the BDC to force the pedal to go through the BDC. Second, the stiffness and stability of the ankle is maintained by activating the tibialis anterior and soleus earlier during downstroke. These two muscles would also be activated slightly through the upstroke phase to transfer the power generated by joint flexion to the crank. Third, the ankle could be in a plantar flexed position for much of the cycling motion with prolonged soleus and gastrocnemius excitation.

Therefore, muscles work in a coordinated way; some work together whilst others work in a coordinated sequence in order to maximize energy transfer from the cyclist to the bike. In this coordinated recruitment pattern, two major areas can be discussed further:

(1) Single-joint muscle activity pattern (e.g. soleus) is different from the multi-joint muscles (e.g. gastrocnemius);
(2) Co-activation is not restricted to the synergistic muscles, the agonist and antagonist muscles (e.g. knee extensors and flexors) also co-activate.

5. Activation patterns for single- and multi-joint muscles

The single-joint muscles were chiefly concerned with the generation of positive work, whereas multi-joint muscles were responsible for the fine regulation of the net moments about the joints (Jacobs, Bobbert, & van Ingen Schenau, 1993). Moreover, the multi-joint muscles served different purposes at different phases of cycling. For example, the rectus femoris assisted flexion of the hip during the recovery phase, but it also assisted knee extension in the propulsive phase (Eisner, Bode, Nyland, & Caborn, 1999). A similar pattern was also observed for the gastrocnemius; during the recovery phase, it functioned as a knee flexor, but during the propulsive phase, it functioned as an ankle stabilizer (Burke, 1995). Rectus femoris and biceps femoris exhibited double bursts of activity at higher cadence. Gregor, Broker, and Ryan (1991) explained that the secondary bursts in these muscles were attributed to their biarticular function.

As the effective ‘downstroke’ only happens within a limited range of crank angles (about 10–170°), activities of the single-joint muscles were consistent across subjects to produce power at a similar portion of the crank cycle. In contrast, the activity patterns in multi-joint muscles were much more variable as they controlled the direction of pedal force produced by the single-joint muscles to adjacent joints; hence their activities were affected by the actions of other muscles (Gregor & Conconi, 2000). The multi-joint muscles were also involved in the transition phase from downstroke to upstroke and vice versa (Mileva & Turner, 2003). Moreover, there may be other factors affecting their activations; for example, the different roles of biceps femoris (hip extensor and/or knee flexor) might be related to subject-specific pedaling techniques and also dependent upon the competitive level.

Relative muscle strength may be another factor, as stronger one-joint hip extensors might be associated with increased rectus femoris activity for power transportation; whereas weaker one-joint hip extensors might need help from bicep femoris to forcefully extend the hip joint (Li & Caldwell, 1998). Increased strength of the single-joint muscles will relieve the load on the synergistic multi-joint muscles, but increase the load on the antagonistic multi-joint muscles. Therefore, the force generated by the single-joint muscle requires the multi-joint muscles to facilitate the energy transfer, and the relative strength of such muscle couples could affect the total energy transferred to the pedals. Therefore, it is very important to balance muscle development when designing muscle training and rehabilitation programs for cyclists

6. Muscle co-activation pattern

During the propulsive phase, several agonist and antagonist muscle pairs activate together to enhance the power acting on the pedal. The plantar flexors (gastrocnemius and soleus) and dorsiflexor (tibialis anterior) could activate together to stabilize the ankle during propulsion and force transmission. Moreover, together with the quadriceps, the hamstring muscles were also active as hip extensors (Jorge & Hull, 1986; Gregor et al., 1991; Gregor & Conconi, 2000). With more detailed studies, a feature of muscle coordination at the hip, knee, and ankle was identified, which was co-activation of one- and two-joint muscles, agonist and antagonist pairs (e.g. gluteus maximus vs. rectus femoris) and the two-joint rectus femoris and gastrocnemius. A functional consequence of this coordination is the transfer of mechanical energy between joints. The one- and two-joint synergists were often co-activated but with a phase shift and time difference in peak occurrence. This occurs because activation of two-joint synergists depends on moment demands at both joints, whereas the activity of one-joint synergists is influenced primarily by the moment demand at only one joint (Prilutsky, 2000).

Smith (1981) stated that the co-activation of agonist and antagonist muscles appeared to be an inherent component in many types of joint movements. Therefore, in addition to just enhancing power output in the propulsive phase, there could be some other functions for the agonist and antagonist muscle co-activation. Aagaard et al. (2000) proposed that during isokinetic knee extension, a neural pathway existed to co-activate the flexors of the knee. This co-activation mechanism may be important for the stability of knee joint as it potentially prevents anterior tibial displacement and assists the mechanical and proprioceptive roles of the anterior cruciate ligament.

Sanderson, Hennig, and Black (2000) noted that if pedal forces were high and cadence was low, eversion of the foot with inward rotation of the tibia through the cycle would lead to stress in the knee. Co-activation of the hamstring muscles may help to relieve this stress. Therefore, co-activation of the agonist and antagonist pairs may serve the purpose of protecting the joints that they act upon. Hunter, St Clair Gibson, Lambert, and Noakes (2002) agreed by stating that the antagonistic activity of biceps femoris would progressively increase to stabilize the knee joint. However, Raasch et al. (1997) stated that it was the plantar flexors that stabilized the knee in late downstroke whilst the hamstrings accelerated the knee towards extension. Therefore, the function of these muscles at different phases of the cycling stroke requires further study.

Muscles activated in a defined pattern are not just for optimizing the energy transfer from the human body to the machine but also provide protection to the major joints, e.g. knees. If any particular muscle becomes too strong or too weak, such optimized muscle activation link might be jeopardized. Hence, identification of weak components in these muscle links and strengthening them with specific muscle training may improve the cycling performance and reduce the risk of injury.

7. Effects of fatigue on muscle recruitment pattern

Muscle fatigue has been defined as the failure of the muscle to maintain the target force (Edwards, 1981). There is, however, considerable controversy about how fatigue is defined and measured. Some experts argue that before this failure point is reached, the muscle is already fatigued (Bigland-Ritchie & Woods, 1984; De Luca, 1984, 1993). Fatigue, from this perspective, is an ongoing process that begins from the start of a muscle contraction. Some people argue that muscle fatigue may be better defined as a time-dependent process with regard to physiological and biochemical changes (De Luca, 1984, 1993).

Electromyographic analysis during fatiguing contractions has been performed extensively on various muscles (De Luca, 1984). During a fatiguing contraction, the EMG amplitude has been found to increase in submaximal contractions (De Luca, 1984; Moritani, Muro, & Nagata, 1986; Krogh-Lund & Jorgenson, 1991). At the same time, changes in the frequency components of the EMG signals can also be observed (De Luca, 1984). There is an increase in the lower frequency components of the EMG spectrum during sustained contractions, and this frequency shift is commonly termed the 'frequency/spectral shift' or 'frequency/spectral compression' toward lower frequency (De Luca, 1984; Hägg, 1992; Ng, Richardson, Kippers, Parnianpour, & Bui, 1996). This frequency shift has been used as an indicator of muscle fatigue (De Luca, 1984, 1993).

Muscle fatigue would decrease the rate of voluntary force development in cycling (Bentley, Smith, Davie, & Zhou, 2000; Lepers, Millet, & Maffiuletti, 2001). Paavolainen, Nummela, Rusko, and Hakkinen (1999) reported that fatigue produced by prolonged and repetitive high-intensity short-duration stretch and shortening cycle exercises could induce acute decrease in force production due to reduced neural input to the muscle and the efficiency of the contractile mechanism. van Dieën, van der Burg, Raaijmakers, and Toussaint (1998) stated that in the dynamic pattern-generation approach, muscles were viewed not as simple effectors operating under neural command but as an integral part of a mutually influencing network with the nervous system. The nervous system adjusted the motor programs in order to compensate for changes of the effector organ characteristics. Such changes could be reduced force output of a particular muscle group due to fatigue. Hence the muscle recruitment in cycling would change due to fatigue. In many studies on cycling, the fatigue process was registered by real-time or continuous monitoring of the rate of decline of pedal power output during maximal cycling workout. With a more detailed study to evaluate the muscular activities at different positions within the pedal revolution, von Tscharner (2002) adopted a time–frequency (wavelet analysis) analysis of EMG signals and found that shifting of the frequency components that occurred with fatigue was very specific for certain periods during the revolution. Some periods had the frequency shift to the relatively high end, while in other periods, the frequency shifted to the lower end. Thus the spectral changes are likely to reflect a systematic change of motor unit recruitment pattern with pedal position and with fatigue.

In order to generate the high force levels accompanying intense activity, maximal or near maximal activation of all the synergistic muscles is a fundamental requirement. It has been found that seven different synergistic muscles were recruited in cycling, their activation pattern being highly ordered and dependent on the limb and pedal positions (Green & Patla, 1992). Muscle activity patterns (i.e. timing) were not significantly affected by changes in pedaling conditions (load, seat height and shoe type) while the only change was the muscle activity levels result from different pedaling conditions (Jorge & Hull, 1986).

On the other hand, Kay et al. (2001) hypothesized that the lower limb inter-muscular recruitment strategies could be altered. During high-intensity cycling exercise, the activities of vastus lateralis and rectus femoris had both increased but vastus lateralis increased more. This could imply a shift of the synergistic muscle recruitment. Moreover, during prolonged exercise at a constant intensity, there were signs that changes occurred in the neuromuscular system as any progress in exercise might influence the efficacy or the pattern with which the contractile machinery was activated (Lepers, Maffiuletti, Rochette, Brugniaux, & Millet, 2002). Therefore, fatigue could affect the pattern of recruitment of the multi-joint muscles. Kay et al. (2001) also found that activation of rectus femoris disappeared after five high-intensity short-sprint cycling strokes. They concluded that although qualitative, their data indicated an alteration in the coordination pattern in cycling movement in conjunction with the development of fatigue.

Hautier et al. (2000) found that muscle coordination in cycling could be efficiently adapted to the loss of the contractile power in the muscles due to local muscle fatigue. For instance, the lower activation of the antagonists after fatigue appeared to be an efficient adaptation of the intermuscular coordination to modulate the net force generated by the fatigued agonist to the pedals for maintaining the force applied to the cycle. With a dynamic cycling study, Prilutsky and Gregor (2000) reported that the fatigue and perceived exertion might be reduced by preferential activation of two joint muscles during phases of movement where they could contribute to the moments at both joints and by reciprocal activation of one-joint antagonists such as soleus or tibialis anterior and two-joint antagonists such as rectus femoris and hamstrings.

Another feature of muscle coordination in cycling, which might potentially reduce fatigue and perceived effort was co-activation of one-joint muscles with their two-joint antagonists. The scenario may be further complicated with the addition of endurance training as Hawley and Stepto (2001) postulated that the number of years of training might improve the patterns of neuromuscular recruitment thus adaptation in response to sport specific overload patterns. Therefore, studies to evaluate the effect of endurance training on the change of muscle recruitment due to fatigue are warranted.

8. Effects of cadence on muscle recruitment pattern

MacIntosh, Neptune, and Horton (2000) concluded that muscle activation at a given power output is minimized at a unique cadence and that cadence increases in unison with power output. As the cadence increased, the time for the recovery phase will decrease and the pedaling leg has to push the recovering leg back to the TDC with a higher force (Sanderson et al., 2000). This will demand more positive force from the pedaling leg thus affecting the muscle recruitment pattern during cycling.

Timmer (1991) and Ericson, Nisell, Arborelius, and Ekholm (1985) noted that increasing the pedaling rate was associated with increased activitiy in the gluteus maximus, gluteus medius, vastus medialis, medial hamstrings, and the calf muscles. In knee extension/flexion, Miller, Croce, and Hutchins (2000) found that biceps femoris would be co-activating more as an antagonist with increasing movement speed. Therefore, with an increasing cadence, the activity of the antagonists may also increase.

Recently, Sarre, Lepers, Maffiuletti, Millet, and Martin (2003) reported no cadence effect on the root mean square EMG value of vastus lateralis and vastus medialis whilst that of rectus femoris was significantly greater at the lowest cadence tested. They attributed this to the increased demand on the rectus femoris to propel the pedal crank anteriorly through the TDC at low cadence. In addition, Gregor et al. (1991) stated that the activities of rectus and biceps femoris progressed earlier in the pedaling cycle as cadence increased, each exhibiting a double burst of activity at higher cadence.

Coyle et al. (1991) demonstrated that a difference in pedaling skill exists even amongst highly trained cyclists. There were large differences in the peak torque during the 'downstroke' when a given work output at the same pedaling rate was performed. This phenomenon was also reported by Takaishi, Yasuda, Ono, and Moritani (1996) who found that the pedaling rate of minimal neuromuscular fatigue at 80 or 90 rpm for non-cyclists was slightly lower than the pedaling rate predicted for experienced cyclists.

9. Effects of posture on muscle recruitment pattern

Standing out of the saddle causes a change in muscle recruitment pattern. The change of body position results in increased muscle activities from 340 to 180° and a cessation of activities from 180 to 280° (Pruitt, 1988). Li and Caldwell (1998) gave a detailed description of the muscle activities during cycling with standing posture. As the pelvis is not supported by the saddle during stand-cycling, gluteus maximus would increase its activity to stabilize the pelvis just before the TDC and this would last well into the latter part of the 'downstroke'.

Brown, Kautz, and Dairaghi (1996) also noted that joint torques and muscle activation patterns observed during pedaling changed systematically with body orientation. Activation patterns of the ankle muscles changed significantly in order to maintain a relatively consistent position of the ankle even late in the upstroke, both net dorsiflexor ankle torque and tibialis anterior activity increased as body orientation became more vertical. However, in this study, the body weight of the subjects was supported by the saddle in all the assessed body orientations. Hence, body weight would not contribute to the pushing force during 'down-downstroke'. The muscle recruitment pattern described in this study may not be applicable to reflect the real picture in stand-cycling.

Miller, Peach, and Keller (2001) examined the muscular activation pattern produced while riding a stepper cycle during sit- and stand-riding. Although the ergometer used in this study was not a normal bicycle, the kinematics of riding the stepper and racing bicycle is similar. Therefore, the information gathered may help to understand the muscle recruitment in stand-cycling. Miller et al. (2001) stated that body weight helps in power production whilst riding in a standing position. The body weight advantage would be lost at low power levels, presumably because the muscular requirements for balance and posture are larger when riding in standing than sitting. From the existing literature, there is no consensus on the optimal power and cadence for stand-cycling.

10. Effects of seat height on muscle recruitment pattern

Seat height or saddle height is the distance between the top of the saddle and the center of the pedal axle measured when the pedal is down and the crank arm is in line with the seat tube. A change of seat height will alter the range of the legs and the muscle length, which would subsequently affect the muscle activity pattern during cycling.

Burke and Pruitt (2003) reported that oxygen consumption in cycling is minimized at approximately 100% of trochanteric height (from the greater trochanter of the femur to the floor whilst standing barefoot), or 106–109% of pubic symphysis height (measured from the ground to the pubic symphysis). However, there is no general agreement on the optimum seat height based on the relationship of muscle activity pattern, joint force and moment patterns, and pedaling effectiveness. Gregor et al. (1991) stated that researchers generally agree that leg muscle activity increases as seat height decreases. This increase appears to be more prevalent in the quadriceps and hamstring muscle groups. Similarly, MacAuley (1995) noted that changes in seat height can alter the balance of the muscle activity. Rectus femoris was found to be more active at a lower seat height of 95% leg length, whilst raising the seat height to 105% leg length increased the activity of the sartorius muscle. Mellion (1991) summarized that for serious cyclists, there are several scientific and quasi-scientific methods for determining the seat height of a bicycle. The more scientific methods are the in seam method, bone length method, and estimation from leg length. All seat height formulae are estimates. After an initial setting is made, the cyclist may fine-tune the seat according to their comfort.

11. Conclusion

There is a well-defined muscle recruitment pattern in cycling. Most studies have focused on the lower extremities and indicated that the hip, knee and ankle generated the power during most of the power phase when all three joints extend. During the recovery phase, these joints flex to pull the pedal back to the top dead center. Mono- and biarticular muscle pairs, agonist and antagonist muscle pairs perform specific functions during cycling, such as diverting the power to the pedal and stabilizing the joints. The muscle recruitment patterns can be altered by muscle fatigue, cadence change and posture. More specific information of the above points will be needed to guide the strength training and rehabilitation programs for cyclists and an optimal specific training module can be developed accordingly.

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