A qualitative analysis of the biomechanics of proper pedal stroke

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A precise qualitative analysis of the biomechanics of proper pedal stroke starts before actual examination of the motion and action during the pedal stroke. First, the overall performance objective (OPO) must be defined. In this analysis, the OPO is performance based and consists of three components; efficiency, power and comfort. All three are intricately related: without comfort, power output and efficiency are compromised; inefficient mechanical position (improper bike fit to athlete) can compromise power output and comfort; lack of power creates inefficiency; etc. Over time and distance each of the components does not wholly exist without the others. Using this information, we then take into consideration the equipment and human constraints to create the correct geometry of bike and athlete; fitting the athlete to the bike for specific cycling disciplines. ***(Road, Time Trial, MTB)*** After fitting, the final step is the athlete to be educated and trained to deliberately generate proper stroke mechanics. The last stage is a comprehensive analysis of the biomechanics of a correct pedal stroke as it applies to the OPO defined.

Our text defines the OPO is the primary goal/focus of a particular movement and the Secondary Performance Objective (SPO) is the objectives(s) other than OPO. *(Floyd 205-207)* For this reason, our discussion of cycling efficiency must begin with the identification of the Overall Performance Objective (OPO) and Secondary Performance Objective (SPO).

Overall Performance Objective

- The maximum (mechanical) efficiency of pedal stroke as it relates to pedaling technique and bike fit

Secondary Performance Objective

- Maximize power (wattage) throughout pedal stroke

Several other important topics will be discussed in the phases of movement section, and are thus worth mentioning here as they relate to the OPO and SPO. The subject of eliminating negative acceleration/torque during the recovery and follow-through portion of the pedaling movement is crucial to the OPO. Secondly, comparing inefficient pedal stroke to a pedal stroke where maximum efficiency (a 'flattening out' of the pedal stroke) is the ultimate goal is discussed in detail throughout the coming sections.

Pedaling efficiency is another definition of note in the discussion of pedal stroke, which is the difference between the human power expended and the actual power delivered to the road. Maximum efficiency can be attained through training of proper pedaling technique and also through a proper 'bike fit' to maximize joint angles of individual. (*Burke)*

The dilemma in biking is that without a proper pedaling technique the 'recovering' leg can actually hold back the 'power' leg. Some of the human energy expended is not transferred directly into the turning of the wheels. Rather, some power is wasted if one leg is holding the other one back during each pedal stroke. (*Lovegren)*

In order to make a qualitative analysis of maximum efficiency of pedal stroke, we will divide the pedal stroke into four individual phases of movement, and then identify the mechanical purpose of each phase**.** We will also discuss what is going on in regards to the muscle activity during each phase. Viewing the motion of pedaling a bicycle can be simplified by considering only one leg at a time, while keeping in mind that the opposite leg will be doing the exact same motions, only in 180 degree opposition. If the right knee is flexing at any given moment, the left knee will be extending at the same moment. Thus, we will consider only the motion of only one leg at a time.

If we view the circular motion of the pedal as if it were the face of a clock, the motion of cycling can be simply broken down into four phases, beginning at approximately the 11 o'clock position:

1. **Preparatory phase** 11:00 to 1:00
2. **Power Phase** 1:00 to 5:00
3. **Follow through Phase** 5:00 to 7:00
4. **Recovery Phase:** 7:00 to 11:00

Note that # 1 and #3 are opposite to each other, as are # 2 and #4. Thus, when one leg is beginning, recovery phase (at 7:00 position), then the opposite leg is beginning the power phase (1:00 position). Similarly, when one leg is beginning preparatory phase, the opposite leg is beginning follow through.

The Preparatory Phase

The preparatory phase prepares the leg and foot for the power phase. This phase begins with the knee in its most flexed position, ready for the 'push' through into the movement phase. During the preparatory phase, the main joint action occurring is knee extension, along with some slight hip flexion and extension as the foot reaches the top and begins back down toward the 1:00 position. Also, the ankle will tend to go from a slightly plantar flexed position at 11:00 to a nearly neutral (pedal level with the ground) at the 1:00 position. Muscles involved in these motions are mentioned in sections below.

The Power Phase

The power phase is the drive, where propulsion comes from. It is the explosion out of preparatory phase (hip beginning in a mostly flexed position). During the power phase, hip and knee extension continue. The most effective force applied is that which is perpendicular to the crank. *(Burke 271)* Clearly, the 3:00 position is the 'peak' of the movement phase, with the large and powerful hip extensors engaging. Muscles involved in hip extension include the hamstrings (semitendinosus, semimembranosus, and biceps femoris), which are biarticular muscles crossing the hip joint as well as the knee joint. Other hip extensors include the gluteus maximus and the adductor magnus. These are both monoarticular muscles, crossing only the hip joint. The adductor magnus has the longest insertion on the femur, giving it the most leverage for hip flexion. However, due to the vertical and medial/lateral correlation between its origin and insertion, there is also external rotation of the knee in its action. Thus, it requires a synergistic force from internal rotators such as sartorius, semimembranosus, and semitendinosus to help counteract the external rotation and keep the leg aligned properly. The gluteus maximus has a similar vertical and medial/lateral correlation to its origin and insertion, and thus a similar tendency towards external rotation. Its hip flexing action is also synergistically assisted by the same internal rotators.

During this same part of the motion, (particularly in the lower part of the movement phase) knee extension is also occurring. The primary knee extensors are the quadriceps: vastus lateralis, vastus intermedialis, vastus medialis and the (biarticular) rectus femoris. Since rectus femoris originates on the ilium, it has the tendency to pull the pelvis into anterior rotation. This rotation shortens the muscle, reducing its ability to produce power. By engaging the abdominal muscles which acts in posterior pelvic rotation, (such as rectus abdominus, the obliques), skilled cyclists will counteract this rotation, thus maximizing the power potential of the rectus femoris muscle. An analysis of muscle utilization of skilled cyclists shows that rectus femoris is utilized strongly through most of the power phase. The vasti muscles produce power most strongly in knee extension during the upper part of the power phase. The ankle joint will ideally remain nearly neutral (pedal level), so that all force applied through this phase will follow a tangential line (perpendicular to the crank). *(Burke 271, 276)*

Follow Through

In many movements, high eccentric contraction takes place during the follow through phase. In cycling however, there needs to be a minimum of deceleration (eccentric contraction) in order to avoid creating drag (inefficiencies in the pedal stroke). This is one of the keys to efficient pedal technique.

As the pedaling foot is moving from 5:00 to 7:00 in follow through, both feet are in the least effective position to produce power (remembering that the opposite foot is moving through the preparatory phase). Continued downward pressure on the pedal puts a force on the crank that is along its axis, rather than perpendicular to it. Instead of downward pressure, it is important during this phase to engage muscles that will put tangential force on the pedal. Cyclists sometimes refer to this part of the motion as the 'scrape', as if the rider is trying to scrape mud off of the bottom of the shoe. The joint action here is knee flexion, with some slight hip extension and flexion as the foot moves through the bottom of the circle and begins upward travel. The primary knee flexors are the hamstrings (semitendinosus, semimembranosus, and biceps femoris). Other flexors are gastrocnemius (biarticulate with the ankle joint) and popliteus, which also rotates the knee internally as it flexes. Antagonists to this action are the quadriceps.

The ankle joint during this phase will begin a slight plantarflexion, helping to keep applied force as nearly tangential as possible. Major plantarflexors include gastrocnemius, soleus, peroneus longus, and peroneus brevis.

Recovery

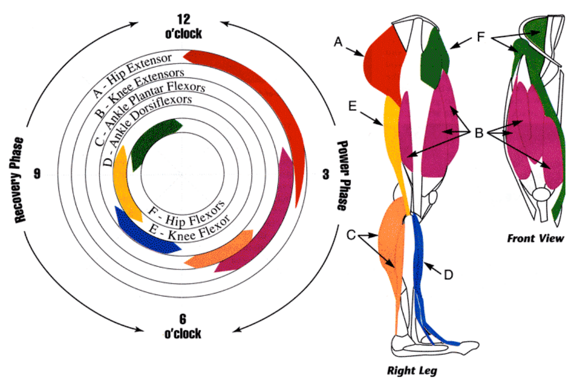
As mentioned above, some of the energy expended by the leg in the power phase will be wasted if it is used to help push the recovering leg up to the top of its phase. In other words, maximum power is not given to propelling to bicycle forward, since some power is given to follow-through phase. This problem is a source of inefficiency in pedaling technique. (Cavanagh; Sanderson)

In the recovery phase of the pedal stroke, (pedal motion from the 7:00 position to the 11:00 position) the primary joint movement at the hip is flexion. The goal here is to minimize any force applied which would be contrary to the power phase which is occurring in the other foot. This primarily involves 'unweighting' of the recovering foot as much as possible through hip flexion. Biarticular hip flexors are the rectus femoris, sartorius, tensor fascia latae and gracilis. Sartorius works both to flex the knee and the hip. Gracilis helps in hip flexion, and also works synergistically to counter the external rotation of sartorius. Other (monoarticular) hip flexors are iliopsoas and pectineus.

The second main joint motion involved in the recovery phase is knee flexion. As mentioned above, this motion involves the hamstrings, gastrocnemeus, and soleus. Antagonistic to these are the quadriceps.

During recovery the ankle joint will continue to be slightly plantarflexed, beginning to move slightly toward neutral (towards dorsiflexion) as it reaches the 11:00 position. This rotation toward neutral (dorsiflexion) will utilize tibealis anterior, extensor hallucis longus, peroneus tertius, and extensor digitorum longus.

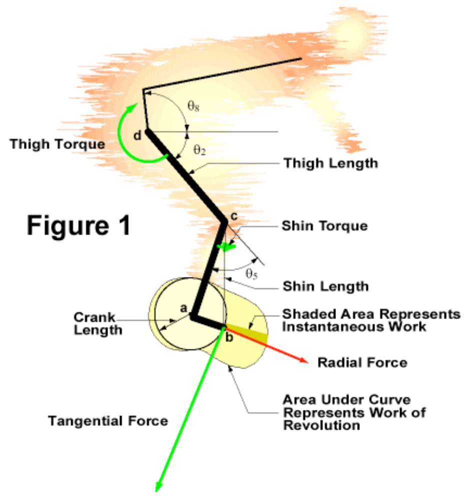
Below is a diagram which highlights various muscle groups described above. Though it is broken down into only two phases (power and recovery) the reader can gain a general idea of the major muscle groups involved in cycling and when during the pedaling stroke they are recruited.
Source: www.nomorecheetos.com



Throughout this section on the phases of movement, muscle action and their relation to pedaling efficiency we mentioned there were several areas where an understanding of cycling biomechanical principles would be crucial. Therefore, a discussion of this topic follows.

This section will identify the biomechanical principles that must be performed in order to achieve the OPO. Correct body position on the bike (i.e. equipment configuration, seat tube angle, correct seat height and the foot placement on the pedal) is all interrelated and are collectively known as the bike fit. For this reason, the bike fit has the outcome of proper muscle recruitment, achievable pedaling rate, power and ultimately maximum pedaling efficiency. *(Gonzales; Hall)*

The bike fit adjusts the angles of the 'levers' of the hip, knee and ankle joints as they relate to the foot-to-pedal interface to achieve the OPO. An improper bike bit will result in reduced efficiency through less than optimal muscle recruitment (improper angles of the levers) and potentially, in serious cases, injuries could result from an improper bike fit.

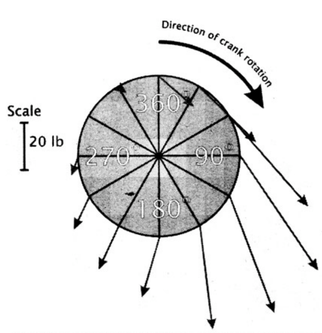


Picture from www.analyticalcycling.com

The above picture is an example of biomechanics at work in the lower body. Notices the levers at the hip, knee, ankle, foot-to-pedal and crank arm. Changing/adjusting angles through the bike fit will create efficiency of pedal stroke.

In other words, adjusting the 'levers' in the bike fit will adjust the forces acting on the crank arm. These forces are the tangential force, otherwise known as divergent force and radial force, or the force that develops uniformally around an axis. These two forces are important because when the pedal stroke power is generated (in the movement phase) these two forces combine to produce torque, which is the force that tends to produce rotation. (*Merriam-Webster's Dictionary)*

The picture below represents the above statement with the pedal stroke. The arrows represent the direction and magnitude of force applied to the pedal.
Picture from www.analyticalcycling.com



Direction and magnitude of forces being applied to the pedal during 360-degree cycle.

Finally, the bike fit must always begin with the individual assessment (i.e. goals, fitness level, biking experience, flexibility, body measurements) then adjust/fit the bicycle to the individual, being sure not to make the common mistake of fitting the individual to the bicycle.

The following is a list of bike fit adjustments/variables:

1. Seat tube angle-correct hip lever angle
2. Seat height-achieve optimal performance height and angle of hip lever.
3. Seat position fore/aft- get knee directly over pedal and correct knee lever angle
4. Adjustment of shoe cleats-Correct knee and ankle lever angle (lateral/medial angle)
5. Handle bar height, reach and size- Maximize hip flexor/extender angle. Correct back and shoulder positioning for comfort and aerodynamics
6. Foot placement on pedal-Correct ankle lever angle at the man/machine interface
7. Crank arm length-needs to be optimum length for cycling purpose
8. Power meter technology to assess bike fit-technology of power meters uses biomechanical technology to assess and improve power and thus performance.

(White)

Biomechanical principles are a very important aspect of cycling. As mentioned earlier the bike fit (perfecting/maximizing the biomechanical principles) must begin with an individual assessment. For example, power, flexibility, strength and endurance are crucial. The following section discusses these ideas as they relate back to the OPO.

Power: "Is the rate at which work is performed or energy is transmitted." *(Wikipedia)*

Good pedal stroke efficiency with respect to speed and power output stems from symmetry between the joints (hip, knee and ankle) on both the left and right side and proper sequence on the down stroke and up stroke or the pushing (extension) and pulling (flexion) of the pedal. The most efficient pedal stroke is created when extension on one side works in conjunction with flexion on the opposite side. When one side does not contribute effectively, the other side does more work to create the same speed and power. This will lead to increased energy expenditure and muscle fatigue resulting in pedal stroke inefficiency and loss of speed/power output.

Flexibility: "Ability to move a joint through full range of motion." *(Wikipedia)*

Flexibility plays a very important roll in pedal stroke efficiency. Flexible muscles are more mechanically efficient and will fatigue at a slower rate then tight, less flexible muscles. Muscles that are tight or have limited range of motion tend to be more susceptible to soft tissue injury and joint strain. As muscles fatigue they become less flexible and therefore provide resistance to the movement of the hip, knee and ankle joints as the pedal rotates. This causes one muscle group to work harder to move the joint because the less flexible, opposing (antagonist) muscle group is resisting the movement. Muscles that are more flexible will offer less resistance as they fatigue.

Strength: "The maximum force a muscle or muscle group can exert during a contraction." *(Wikipedia)*

Upper body and core strengths are crucial in providing proper posture and maximum power output. Core strength is important due to the rider's bent over position for an extended period of time, which can lead to poor posture and increased muscle fatigue. A strong core also provides rigidity to deliver maximum power from the quadriceps and hamstrings to the pedal.

Endurance: "Ability to maintain a specific power level, involving muscular contractions for a given period of time." *(Wikipedia)*

Muscle endurance is also extremely important in maintaining pedal stroke efficiency. In order to maintain a smooth continuous pedal stroke the muscles will need to continuously contract to creating muscle movement. For muscle contraction to occur the muscle must receive the basic unit of cellular energy, adenosine tri-phosphate (ATP), which is metabolized in the mitochondria. An increase in size and number of mitochondria will allow for more energy production to occur therefore resulting in an increase in muscular endurance. Sustained aerobic training has been shown to increase the size and number of mitochondria in the muscle cells by as much as 200%.

Constraints

In cycling, two type of constraints influence a cyclist performance - event constraints (also known as environmental factors) and human constraints (also known as physiological and psychological factors). *(Sports Med)*

Event constraints, subsuming the environment itself on the one hand and the physical modalities of the bike on the other, directly affect power and speed. Purely environmental factors include ambient weather, distance, race rules, and trail or race course characteristics. Bike related aspects comprise pedals, pedal clips, chain and gear type and condition, handle bars, brakes, and aerodynamic attributes. In addition to these constraints, there are also cyclist related determinants such as bike fit and type of cyclist clothing. All of these are generally known as outside factors.

Conversely, cycling's inside factors deal directly with the human condition. *(Faria E., Faria I., Parker)* Human constraints are either physiological or psychological. Physiological constraints can include proper nutrition, VO2max, training regimen, physical strength, and skill level. Psychological constraints come down to how the cyclist perceives his or her own abilities and potential. A positive mind set, an optimistic frame of reference, and a realistic strategy all contribute to increased chances for success.

Therefore, superior performance preparation requires a realistic assessment of the cyclist's strengths and weaknesses, i.e. - physiological and psychological constraints.

Skill

The sport of cycling can alternatively be viewed as either an open skill or a closed skill. Cycling proper is considered an open skill because the environment around the cyclist is changing all the time. For example, the cyclist has to be able to quickly adjust and respond to road hazards or unexpected conditions when riding outside. Even the course itself can frequently change from uphill to downhill, from straights to curves, and from dry to wet. Because of this unpredictability, outdoor cycling can be described as an open skill.

Pedaling, an integral and requisite action at the very core of cycling, is a closed skill. The pedaling motion is constant and predictable, repeating itself over and over again. Even as the environment changes, the dynamics and mechanics of pedaling remain the same.

Cycling is therefore both a continuous (no separation from beginning to end) and a hybrid (at once a closed and an open skill) paradigm. Competitive cycling is mentally challenging, physiologically demanding, and physically draining. Understandably, then, there is only one Lance Armstrong.

Relationship between Critical Features

As defined, the OPO has several critical factors that follow a necessary sequential pattern, each vital in creating a foundation for the next, all based on achieving the primary, secondary and minor objectives. Each of these objectives in turn all point back to the optimum performance objective. The primary OPO is as follows; maximum (mechanical) efficiency of pedal stroke as it relates to pedaling technique and bike fit, so physically fitting the bike to the cyclist is a key prerequisite. In appropriately fitting an athlete factors considered are comfort, flexibility of tendons and muscles, proper angular fit, and correct stroke and cadence mechanics by the cyclist. The pursuant identification of joint movement and muscle action then provides the most advantageous data for the performance based objectives.

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