The Biomechanics of Force and Power Production in Human Powered Vehicles

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Abstract

There are a large number of factors affecting performance in human powered vehicles (HPV). Designers of HPV's often focus on how resistive forces (friction, drag) can be minimized, as opposed to how propulsive forces can be maximized. How to maximize propulsive forces through vehicle design is not often understood because of a complex interaction between internal biomechanical factors (muscle force/torque/power production) and external mechanical factors (e.g., seat-to-pedal distance, crank arm length, seat-tube angle, backrest angle, chain wheel size). The purpose of this paper is two-fold: (1) to provide information, from a biomechanical and physiological perspective, how muscle force is produced and modified; and (2) to examine how the muscle force produced interacts with external mechanical factors to produce power.

Introduction

Speed and performance in land based HPVs are a function of the amount of propulsive forces produced versus the amount of resistive forces that need to be overcome. Designers of HPVs often focus on minimizing resistive forces (drag and rolling resistance) in the construction of a vehicle. This would include reducing vehicle cross-sectional area, the surface area, and drag coefficient to decrease aerodynamic drag. To decrease rolling resistance, vehicle and rider weight would be reduced, and the wheel and tire properties modified (e.g., using a larger wheel diameter, greater tire pressure, etc.). Since aerodynamic drag forces have a greater effect on speed than rolling resistance, the design and construction of HPVs have focused predominantly on how to minimize drag forces. A vehicle is often constructed first, with the objective to minimize drag, and then a rider is selected to fit in the vehicle - without consideration as to whether the rider is in the most effective seating position to maximize force and power production.

In attempts to increase propulsive force, designers will modify or manipulate external mechanical factors such as crank arm length, seat-to-pedal distance, seat-tube angle, backrest angle, chain wheel size, and gear ratio (and/or select bigger and more powerful riders, such as competitive cyclists or world class athletes), without really understanding how muscle force is generated, modified and might interact with these external mechanical factors. Modifications of these mechanical factors are often done intuitively or randomly, without empirical data to support the variable(s) that should be manipulated, the extent of these manipulations, and whether some variables might interact with other variables to affect power production. Therefore, depending on the design of the vehicle, the rider could be seated in any number of cycling positions, with different body orientations and joint configurations, pedaling with any combination of crank arm length, seat-to-pedal distance, seat-tube angle, backrest angle, and chain wheel size - without scientific evidence as to what factors and/or combination of factors will maximize propulsive forces. This is thus the reason for such diversity in HPVs. It should be noted that the optimum parameter (e.g., crank arm length and/or seat-to-pedal distance) to maximize power for one cyclist (determined from trial and error) might not be optimum for another, especially when cyclists have different anthropometrical characteristics (in height, leg length, thigh/leg length ratio, etc). To provide information to designers of HPVs about how and why seating position may affect propulsive forces, a review of how muscle force and power are produced and modified, will be provided.

Force-Length Relationship

Based on the force-length relationship, a muscle can produce it's greatest force at it's resting length. At resting length, an optimal overlap occurs between the muscle contractile elements (actin and myosin filaments) resulting in a maximum number of cross bridges that can be formed. With increasing or decreasing muscle lengths from resting length (such as when a muscle is lengthening or shortening during a pedal cycle), the force a muscle can produce will decrease. Therefore, an inverted U-shape curve best describes the force a muscle can produce with increasing length from it's minimum length to resting length, and then from resting length to it's maximum length (see Figure 1).

For single joint muscles, the joint angle corresponding to this resting length can be determined experimentally using an isokinetic dynanometer or using maximal isometric contractions at different joint angles throughout the joint range of motion. However, for multi-joint muscles, it is much more difficult and complex to determine the joint angle(s) at which resting length and maximum force production occur at. For example, the rectus femoris is a two-joint muscle that crosses the hip and knee and is involved in flexion of the hip and extension of the knee. If maximal isometric knee extension strength is measured when the hip and knee are both at 90 degrees of flexion (such as the starting position for

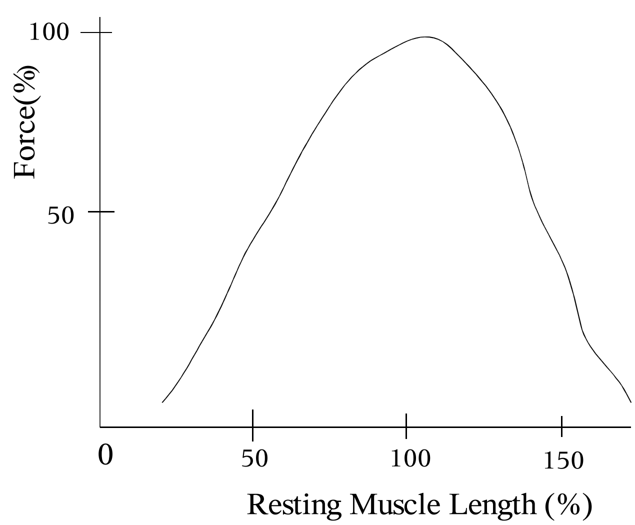

Figure 1: Force-Length Relationship

performing a leg extension when seated in an upright position), the force produced by the rectus femoris will change if the hip angle is changed (such as when leaning forward or backwards during the isometric contraction). Changes in hip angle (with hip flexion or extension) will change the length of the rectus femoris (shortening or lengthening it) and alter it's maximum force produced at the knee. Conversely, if the hip angle is fixed and the knee angle is free to vary, different maximum isometric forces will be observed with different knee angles (due to different muscle lengths of the rectus femoris). Complexity is further increased when, both the hip and knee angles change simultaneously during a dynamic contraction, such as in a squat or leg press. During a squat or leg press, when both the knees and hips are extending during the extension (pushing) phase of the squat or leg press, the rectus femoris would be shortening at the knee while lengthening at the hip. During this phase, the muscle length (and force produced) could remain the same or change, depending on whether the hip and knee are extending simultaneously, synchronously, asynchronously, and/or have the same change in angles. A similar analogy can be made to cycling.

In cycling, there are multi-joint muscles (hamstrings, rectus femoris, sartorius, gracilis) acting at the hip and knee, and knee and ankle (gastrocnemius, plantaris) to produce force during a pedal cycle. The hip, knee, and ankle joint angles (resulting in resting muscle lengths) that maximize force production during a pedal cycle are unknown. During the propulsive phase in cycling, both the hip and knee are extending. The hip and knee angles that might maximize hamstring force production (during hip extension when cycling) may not be the same angles to maximize rectus femoris force production at the knee (during knee extension). Knowing (or not knowing) the specific joint angles that would maximize force production during a pedal cycle is probably not that important if cyclists were constrained to pedal in the same seating position. For example, if a selected seating position (e.g., standard upright cycling position) results in joint angles that are fairly efficient (or inefficient) for one individual, it would probably result in joint angles that are similarly efficient (or inefficient) for others. But if two dissimilar cycling positions are used (e.g., a high upright sitting position versus a low recumbent sitting position), one cycling position may result in greater production of power due to more effective joint angles (from more optimal muscle lengths) than the other. In this case, information about the specific joint angles that would maximize force production during a pedal cycle is important if cycling performance is to be maximized.

Seat-to-Pedal Distance

If some seating position (e.g., standard upright) is selected regardless of whether it results in effective or ineffective muscle lengths and joint angles, and a standard crank arm length is used, the only manipulation to change hip, knee, and ankle angles, would be changes in seat-to-pedal distance (seat height). Of course the cyclist could shift the saddle-seat location a bit, or lean forward to rest on the handlebars, or sit more upright, to manipulate the hip angle. But this change in hip angle would be minimal compared to the change that would occur with changes in seat height. If the seat height is changed, the minimum and maximum angle of the hip and knee will change, although the range of motion at the hip and knee will remain the same. This would mean that with changes in seat height, contraction of the muscles would occur in different regions of the force/tension-length curve during a pedal cycle (although the amount of muscle shortening/lengthening would remain the same). Maximum force production would then occur with a seat height where muscle contraction corresponds to the portion of the force/tension-length curve closest to resting length (or at resting length). This is supported by studies that reveal an optimum seat height to maximize cycling performance in aerobic and anaerobic tests (Gregor & Rugg, 1986; Nordeen-Snyder, 1977; Shennum & deVries, 1976; Thomas, 1967; Too, 1993).

However, this traditional upright cycling position with specified joint angles (minimum, maximum and range of motion) for the hip, knee, and ankle (dictated by the seat height and standard crank arm length) during a pedal cycle might not be the most effective position to produce force. The most effective position may be a non-traditional cycling position (i.e., recumbent) that utilizes joint angles and muscle lengths (for both single and multi-joint muscles) that correspond to the resting length portion of the force/tension-length curve (Too, 1996). This is supported by studies where hip angles (minimum and maximum) were systematically manipulated (through changes in seat-tube-angle, using 5 positions ranging from a high sitting upright position with the hips above the pedals, to a low sitting position with the hips below the pedals) while the knee angles (minimum, maximum, range of motion) were controlled (Too, 1991, 1990).

Joint Angles, Muscle Length, and Crank Arm Length

Unlike changes in seat-to-pedal distance with a fixed crank arm length, a change in crank arm length with a fixed seat-to-pedal distance will result in a change in the range of motion during a pedal cycle at the hip and knee (Too & Landwer, 1999, 2000; Too & Williams, 2000). In addition, the minimum and maximum hip and knee angle will also change unless the seat-to-pedal distance is determined from maximal extension of the hip and knee during one pedal cycle. In this case, the maximum hip and knee angle will not change with changes in crank arm length whereas the minimum and range of motion will change. This presents greater complexity in determining the joint angles and range of angles at the hip and knee that would maximize force production because: (1) with changes in crank arm length, the amount of muscle shortening and lengthening would change, and depending on whether the crank arm length was increased or decreased, contraction of the muscles would occur over greater or lesser portions of the force/tension-length curve during a pedal cycle; and (2) with an increased crank arm length, a greater torque can be produced at the crank spindle with the same force (or the same torque can be produced with a smaller force). The interaction between the force produced at different muscle lengths - during a pedal cycle when different crank arm lengths are used - with the length of the crank arm, will ultimately determine the torque which can be produced at the crank spindle. Of course, the resulting interactions to produce force and torque would be even more complex if different combinations of seat-to-pedal distances, crank arm lengths, and seat-tube-angles were used, resulting in an extremely large number of combinations of joint angles (minimum, maximum, range of motion) and muscle lengths at the hip, knee, and ankle. It should be noted that it is not the actual seat-to-pedal distances, crank arm lengths, and seat-tube-angles that are important in maximizing force and torque. Instead, it is the resulting hip, knee, and ankle angles from the combined interactions of these external mechanical variables that correspond to the portion of the force-length curve closest to resting length to produce the force that will maximize torque and power production.

Force-Velocity-Power Relationship

Based on the force-velocity relationship, the force a muscle can produce will be affected by it's velocity of contraction. With a high velocity of contraction (and no load), minimum muscle force (and power) can be produced because the actin and myosin filaments would be sliding by each other faster than the cross bridges that can be formed and activated. As the load increases, the velocity of contraction decreases, and with a maximum load, the force of contraction becomes a maximal isometric one (resulting in zero power) (see Figure 2). Since power is a function of force and velocity, based on the force-velocity-power relationship, maximum power appears to be obtained with a load and velocity that is one third to two thirds of the maximum muscle force and velocity of contraction that can be produced.

From the force-velocity-power relationship, maximum power (or a desired power output) in cycling can be obtained with numerous combinations of load (chain wheel size, gear ratio) and velocity (pedaling frequency). However, it should be noted that there is not only an interaction between force (load), velocity (pedaling rate), and power, but also with muscle length. Depending on the muscle length with different cycling positions (i.e., upright or recumbent), the optimum combination of load and velocity to maximize power output is unknown and may vary with different cycling positions. This complexity is further increased if the crank arm length is manipulated.

Power Output, Load, and Pedaling Frequency

A change in crank arm length will not only affect force production by the hip and knee, by changing joint angles (minimum, maximum, range of motion) affecting muscle length, but it will also affect the torque produced at the crank spindle, the load that can be applied, the maximal pedaling frequency, and the resulting interactions in the production of power. For example, when compared to a long crank arm, a shorter crank arm will not only reduce the minimum, maximum, and joint range of motion at the hip and knee over one pedal cycle affecting muscle force production, but it will also result in a reduced torque (if the same force is applied) at the pedals. However, because of the shorter crank arm, there is a potential for a greater maximal pedaling frequency. Whether this greater maximal pedaling frequency can be obtained, will then be dependent on the load (gear ratio, chain wheel size) and resistance that needs to be overcome.

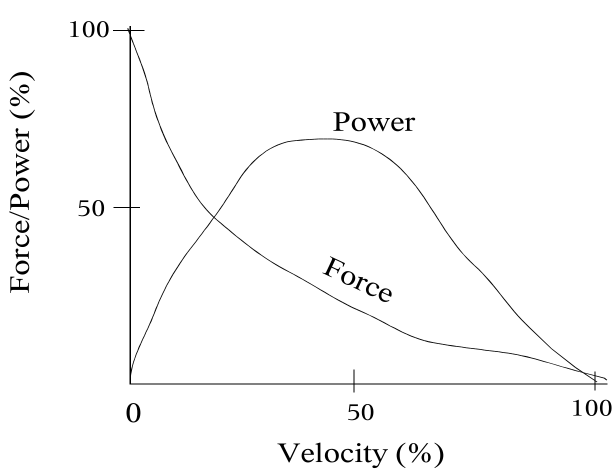

Figure 2. Force-Velocity-Power Relationship

According to Seabury, Adams, and Ramey (1977), (1) there is a most efficient pedaling rate for each power output; (2) the most efficient pedaling rate increases with power output; (3) the increase in energy expenditure when pedaling slower than optimal is greater at high power outputs than at low power outputs; and (4) the increase in energy expenditure when pedaling faster than optimal is greater at low power outputs than at high power outputs. This would suggest that if a given sustained power output is required to set a new distance record in some human powered vehicle event (such as the hour record or 24 hour record), it becomes important to know not just what is the optimal pedaling rate, but also the interaction of pedaling rate with crank arm length and load, in order to maximize power output, yet minimize energy expenditure and muscle fatigue.

On the other hand, to maximize performance of human powered vehicles for short distances (200 meter sprint) and set new speed records, a great deal of power would be required but only for a short period of time. To maximize this power, it is desirable to maximize both, force (i.e., load, gear ratio) and velocity (pedaling frequency). However, according to the force-velocity-power relationship, increasing force (load) to a maximum value will result in a decreasing contraction velocity (pedaling rate) to a minimum value. Therefore, with a fixed crank arm length, the maximum power appears to be obtained with a load and velocity that is 1/3-2/3 the maximum muscle force and velocity of contraction that can be produced. If the crank arm length is free to vary, the interaction between force (in this case, it would be torque) and velocity to produce maximum power, would be more complex. With a given force, the torque applied to the crank spindle would be less for a shorter crank arm, but the maximum pedaling rate would be greater. Conversely, with a given force, the torque applied to the crank spindle would be greater for a longer crank arm - and a greater maximum load can be used - but the maximum pedaling rate would be lower when compared to a shorter crank arm. To maximize power with increasing load, force and torque would also have to increase, assuming pedaling rate is already at a maximum. However, according to the force-velocity-power relationship, as load continually increases, there will be a critical load beyond which will result a decrement in velocity (pedaling rate), and this would be especially true for shorter cranks. With longer crank arms, greater loads can be used because greater torques can be produced, and due to the decreased maximal pedaling rate for longer cranks, the critical load beyond which will result in a decrement in velocity (pedaling rate) will be much greater than that expected for shorter crank arms. What is the critical load for different crank arm lengths (short and long), beyond which there will be a decrement in pedaling rate and/or power, is unknown. What is the optimal combination(s) of load and pedaling cadence for different crank arm lengths to maximize power production or to minimize the energy requirement for a given power output are also unknown. Of course this complexity is increased with the interaction of other factors (such as changes in seat-to-pedal distances, seating positions, etc.)

Other Considerations

Body orientation (trunk angle) with respect to the ground, and location of the lower extremities relative to the crank spindle are additional factors that need to be considered because of their possible effect on force production and total force contribution to the pedals in cycling. Changes in body orientation (trunk angle) will affect muscle force/tension-length relationships and force production if it results in hip angle changes. Changes in body orientation (trunk angle) without changes in hip angle may affect the body weight contribution to the force on the pedals (depending on the location of the lower extremities to the crank spindle). For example, a cyclist in a standard upright bicycle would have the leg weight contributing to the total force on the pedals during the power stroke. However, if a cyclist was in a reclining/recumbent position where the lower extremities were below the crank spindle (e.g., cycling in an inverted position), work would have to be done in not just overcoming the cycle resistance/load, but also in overcoming the weight of the lower limbs when pedaling-working against gravity, resulting in less total force applied to the pedals during the power/pushing stroke. Too (1989, 1994) determined that changing the body orientation (trunk angle) with respect to the ground does affect peak power production and power output. In fact, if cycling in a completely inverted position, it would probably be easier and more effective to pull against the pedals during the recovery phase (using the leg weight when it is aided by gravity) than during the power phase (where work would have to be done against gravity to overcome the lower limb weight). This would explain why recumbent bicycles are less effective in climbing hills when compared to the standard upright bicycle. Low sitting position recumbent vehicles that have pedals located above the cyclist's hip, require the cyclist to pedal upwards against gravity (to overcome some portion of their leg weight) during the power stroke. When climbing hills (and depending on the angle of the hill), the cyclist would need to overcome an even greater proportion of the lower limb weight during the power stroke, and thus requires an even greater expenditure of energy.

Summary and Concluding Remarks

As the limits of engineering design in HPVs to minimize resistive forces are reached, it becomes essential to focus on maximizing the propulsive forces. This requires an examination of the human engine powering the vehicle and how to maximize it's efficiency. This necessitates not just an understanding of how muscle force is produced (based on force/tension-length and force-velocity-power relationships), but also how they interact with external mechanical variables such as seat-to-pedal distance, seat-tube angle, and crank arm length to alter lower extremity joint angles (hip, knee, ankle), affecting force and power production. It should be noted that it is not the manipulation of the external mechanical variables that is important, but rather how the manipulation affects joint angles of the hip, knee, and ankle during the pedaling action. The question should *not* be "what is the optimal crank arm length or seat-to-pedal distance to maximize force and power production?" but rather "what are the joint angles that would maximize force and power production, and what manipulations in HPV design should be done to obtain these joint angles?" It should also be noted that the optimal crank arm length for a very tall individual will probably not be optimal for a very short individual, whereas the joint angles to maximize force and power will probably be similar for both the tall and short individual. It is beyond the scope of this paper to review the existing literature involving manipulations in external mechanical variables and the resulting effects on joint angles and cycling performance. However, that would be a topic for a future paper.

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