OPTIMIZATION OF THE SEATING POSITION IN A HUMAN-POWERED VEHICLE

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INTRODUCTION

Until recently, most of the human-powered vehicles (HPV) were designed focusing solely on its aerodynamics characteristic. In many of these HPV designs, the rider seating position was arbitrarily chosen without consideration of its effect on the rider's comfort and cycling effectiveness. Also, there is no guarantee that the seating position is related to maximum power output. Too (1991) used an experimental approach to determine that the rider will produce the maximum anaerobic power when the seat tube angle of a bicycle is at 75° whereas Hull and Gonzalez (1990) used an engineering approach to optimize the cycling biomechanics. However several factors, including aerodynamic effects, were not considered in both studies. The objective of this study was, therefore, to find the optimal rider's seating position in HPV for either aerobic or anaerobic performance. The method is based on modeling a mechanism equivalent to the hip, knee, and ankle joints. All physical constraints on the motion of these three joints as well as the HPV design constraints are mathematically described. Nonlinear programming techniques were used to reach an optimal solution for either aerobic or anaerobic designs. To test the validity of the model, it was compared to the experimental results of the anaerobic cycling power test presented by Too (1991).

MODELING THE DYNAMICS OF THE HIP AND KNEE JOINTS

Figure 1 shows a schematic of the HPV riding position. For simplification, the angle between the foot and the shank is assumed to be fixed at 90° during pedaling. Therefore, hip, knee, pedal, and crank comprise a four-bar linkage of the crank-rocker type. The displacement, velocity, and acceleration equations for such mechanisms are readily available in the literature (Erdman and Sandor, 1991). As a result, calculation can be made of the torque required at both the hip and knee joints of the rider as a function of the HPV speed, aerodynamic coefficient, and rolling friction.

The required power input from the rider depends on the weight of the vehicle and rider, the target speed of the HPV, the sum of the rolling resistance of the wheels, and the air-drag resistance expressed as:

$$\text{Power} = (\mu(W_{hpv} + W_{rider}) + 1/2\, C_d \rho\, V_{hpv} A_{hpv})V_{hpv} = 2Fn\, r_2\, \omega_2 \tag{1}$$

If it is assumed that the vehicle has an elliptical cross section, A_{hpv} is equal to:

$$A_{hpv} = 1/4\ \pi\, W_{hpv}\,(r_{up} \sin\theta_b + r_1 \sin\theta_1) \tag{2}$$

The width of the HPV, W_{hpv}, is dependent on the elbow to elbow distance of the rider. Substituting equation (2) in (1), the torque required to drive the vehicle at a given velocity is determined. Once the normal force on the crank is calculated, the corresponding moments on the knee and the hip joints can be determined. Inertia and gravity effects are included in these expressions. The moment equations for the knee and the hip joints are:

$$M_k = -(I_s + m_s r^2_{scg})\,\alpha_3 - (I_f + m_f r^2_{fcg})\alpha_3 - Fn\, r_3 \cos(\theta_2 + \theta_3) + m_s\, r_{scg} \cos(\theta_3 - \delta_f) + m_f\, r_{fcg}\, g \cos(\theta_3 - \delta d_f) \tag{3}$$

$$M_h = -(I_t + m_t r^2_{tcg})\,\alpha_4 + M_k + m_t\, r_{tcg}\, g \cos\theta_4 \tag{4}$$

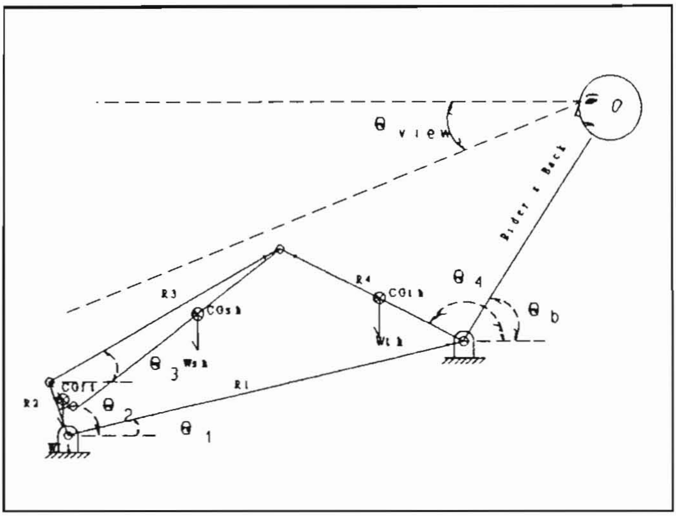

Figure 1. Schematic of HPV riding position.

OPTIMIZATION OF THE SEATING POSITION IN HPV

HPV can be designed for either aerobic or anaerobic optimal performance. We assume that the vehicle is at a target speed and the crank rotational velocity is fixed in both designs. In the aerobic design, the objective function is to minimize both the average and the maximum variation of the moments on the hip and the knee joints. In the anaerobic design, the objective function is to minimize the moment variations on the hip and the knee joints. The design variables are: θ_b, θ_1, r_1, and r_2.

The objective function for aerobic design is to minimize the average and amplitude of the moments at the knee and hip joints as follows. For the anaerobic design, the objective function is:

$$F_{obj} = \frac{\sqrt{\Sigma M^2_{ki}} + \sqrt{\Sigma M^2_{hi}}}{N} + \frac{\Sigma M_{ki} + \Sigma M_h}{N} \tag{5}$$

The search for optimal solution in both cases is constrained by:

$$F_{obj} = ABS(M_{knmax} - M_{knmin}) + ABS(M_{hpmax} - M_{hpmin}) \tag{6}$$

1) conditions to ensure that the seat to crank position results in full rotation of the crank.

$r_1 \geq r_2$ $\quad$ $r_3 \geq r_2$ $\quad$ $r_4 \geq r_2$ $\quad$ $r_4 + r_3 \geq r_1 + r_2$

$r_1 \geq r_4$ $\quad$ $r_1 \geq r_3$

2) motion limits of the knee joint,

$\theta_4 - \theta_3 \leq 175°$ $\quad$ $\theta_4 - \theta_3 \geq 35°$

3) motion limits of the hip joint,

$\theta_4 - \theta_b \leq 175°$ $\theta_4 - \theta_b \geq 58°$

4) visibility of the road that limits how far the seat can be inclined for safe driving,

$\theta_b \geq 10°$ $\theta_b \leq 180°$

5) minimum acceptable crank length,

$r_2 \geq 0.03$ m

6) minimum acceptable seat to crank distance,

$r_1 \geq 0.3$ m

7) allowable range of seat tube angle,

$\theta_1 \geq -90°$ $\theta_1 \leq 90°$

The target speed of HPV is 40.0 km/hr, and the vehicle weight 50.0 kg with the air drag coefficient of 0.15 and wheel rolling friction of 0.01. The crank angular speed is one revolution per second. Also the rider of this HPV is assumed to be at the 50th percentile of U.S. males (Woodson, 1981). The objective function was minimized by successive quadratic approximation method (Rekalitis et al., 1983).

RESULTS

The optimal aerobic performance is achieved when,

$\theta_b = 26.72°$ $\theta_1 = -5.70°$

$r_1 = 0.750$ m $r_2 = 0.15$ m.

The optimal anaerobic performance is achieved when,

$\theta_b = 48.1°$ $\theta_1 = -25.4°$

$r_1 = 0.751$ m $r_2 = 0.15$ m.

From these results, the following statements can be made:

1) Optimal aerobic and anaerobic designs occur when the seat to crank distance reaches the limit of the rider's leg length.

2) Optimal performance is associated with long crank arm length since normal force, Fn, is inversely proportional to crank arm length, r_2. However, r_2 cannot be extended indefinitely since it will start interfering with the first set of constraints listed in the preceding section.

3) Due to aerodynamic effect, the lower the height of the vehicle, the less resistance the rider has to overcome. However, poor viewing angle on the road limits the minimum possible angle of θ_b.

4) The optimal anaerobic design differs from the aerobic design in having greater seat angle since the objective function is formulated in a way stressing momentary peak performance compared to long duration steady performance as in aerobic design.

To validate the model, the anaerobic design was compared to the experimental data of Too (1991) for maximum anaerobic performance of a stationary bike. This comparison was done when the aerodynamic effects were not present. The same human input data as reported by Too (1991) was used. Only two variables were used. They are q_1 and r_1. The remaining variables were set to fixed values. The constraints are the same as listed in the previous section. The optimal results were:

$\theta_1 = 22.9°$ $r_1 = 0.662$ m.

The variables used by Too (1991) can be related to those used in this study as follows:

$$\text{seat tube angle} = 90° - \theta_1 \qquad (7)$$

Results for maximum anaerobic power obtained by Too (1991) were:

$\theta_1 = 15°$ $r_1 = 0.6655$ m.

The above data show close similarity between experimental and analytical solutions.

Inspecting Figure 2 in Too (1991) shows that the maximum anaerobic power occurs when q_1 is greater that 15°. These results may be tuned by collecting more experimental data.

CONCLUSIONS

A scheme for determining the optimal seating position in a human-powered vehicle was proposed. This method can be used to obtain either maximum aerobic or anaerobic power. Modeling the dynamics of knee and hip joints in cycling is included. This model optimized the seating position by varying the back angle, the seat to pedal position, the seat to pedal length, and the crank length. The optimization is subject to various constraints to ensure mobility and safe driving of the vehicle as well as various vehicle design considerations. The optimal design resulted in a low profile vehicle with the foot almost in full extension. Comparison with experimental results for maximum anaerobic power of a stationary bike showed reasonable agreement. The results presented here need further experimental verification. Engineering optimization techniques could be further used in different sports applications.

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NOMENCLATURE

A_{hpv} - Front area of the vehicle
Fn - Normal force applied to the crank
I_t - Moment of inertia of the thigh
I_s - Moment of inertia of the shank
I_f - Moment of inertia of the foot
m_t, m_s, m_f - Mass of the rider's thigh, shank, and foot, respectively
r_1 - Seat to crank distance
r_2 - Crank arm length
r_3 - Knee to pedal distance (when ankle joint is fixed at 90°)
r_4 - Thigh to knee distance
r_{up} - Upper body length
r_{tcg} - Distance between the thigh center of gravity and hip joint
r_{scg} - Distance between the shank center of gravity and the knee joint

r_{fcg} - Distance between the foot center of gravity and the knee joint (when the ankle joint is fixed at 90°)
V_{hpv} - Vehicle target speed
w_{hpv} - Width of the HPV
W_{hpv} - Weight of the HPV
W_{rider} - Weight of the rider
δ_f - Angle between rfcg and r3
δ_s - Angle between rscg and r3
θ_b - Rider's back support angle
θ_1 - Seat tube angle
θ_2 - Angle of the crank
ω_2 - Angular velocity of the crank
ω_w - The angular velocity of the driving wheel