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The Influence of Seat Configuration on Maximal Average Crank Power During Pedaling: A Simulation Study

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Manipulating seat configuration (i.e., seat tube angle, seat height and pelvic orientation) alters the bicycle-rider geometry, which influences lower extremity muscle kinematics and ultimately muscle force and power generation during pedaling. Previous studies have sought to identify the optimal configuration, but isolating the effects of specific variables on rider performance from the confounding effect of rider adaptation makes such studies challenging. Of particular interest is the influence of seat tube angle on rider performance, as seat tube angle varies across riding disciplines (e.g., road racers vs. triathletes). The goals of the current study were to use muscle-actuated forward dynamics simulations of pedaling to 1) identify the overall optimal seat configuration that produces maximum crank power and 2) systematically vary seat tube angle to assess how it influences maximum crank power. The simulations showed that a seat height of 0.76 m (or 102% greater than trochanter height), seat tube angle of 85.1 deg, and pelvic orientation of 20.5 deg placed the major power-producing muscles on more favorable regions of the intrinsic force-length-velocity relationships to generate a maximum average crank power of 981 W. However, seat tube angle had little influence on crank power, with maximal values varying at most by 1% across a wide range of seat tube angles (65 to 110 deg). The similar power values across the wide range of seat tube angles were the result of nearly identical joint kinematics, which occurred using a similar optimal seat height and pelvic orientation while systematically shifting the pedal angle with increasing seat tube angles.

Keywords: forward dynamics simulation, design optimization, bicycle setup, cycling

Previous studies have investigated the influence of training techniques, equipment design, and equipment setup on cycling performance (for a review, see Faria et al., 2005a, 2005b). Of these factors, aerodynamic drag has been identified to have a great influence on cycling performance and recent studies have investigated the effect of altering different aspects of bicycle helmet (e.g., vent orientation, surface roughness) and bicycle design (e.g., wheel type) on the drag forces (e.g., Alam et al., 2008; Lukes et al., 2005). However, the development of novel equipment and training techniques can be time consuming and costly. As a result, other studies have focused on optimizing existing equipment setup to improve performance such as altering foot placement on the pedal (Van Sickle & Hull, 2007) or rider position (Garcia-Lopez et al., 2008). Modifying equipment setup can alter bicycle-rider geometry to reduce aerodynamic drag and alter lower extremity kinematics to take advantage of intrinsic muscle force-length-velocity relationships and increase muscle power output.

Preferred seat configuration (i.e., seat height, seat tube angle and pelvic orientation) can vary greatly between individual riders and racing disciplines. A number of studies have investigated the influence of seat configuration on lower limb kinematics and kinetics (e.g., de Groot et al., 1994; Savelberg et al., 2003) and performance metrics such as metabolic cost (e.g., Gnehm et al., 1997; Grappe et al., 1998; Welbergen & Clijsen, 1990), muscle activity (e.g., Savelberg et al., 2003; Silder et al., 2009), and power output (e.g., Reiser et al., 2002; Too, 1991; Umberger et al., 1998) . Both seat height and pelvic orientation have been shown to alter lower extremity kinematics and muscle function during pedaling. For example, varying seat height alters both the minimum and maximum angles at the knee and ankle joints (Price and Donne 1997) as well as at the hip joint (Nordeen-Snyder 1977) during steady-state, submaximal pedaling. Both studies also observed changes in oxygen consumption at different seat heights, suggesting that changes in kinematics associated with varying seat height influences muscle power generation. Other studies have investigated the influence of pelvic orientation on lower extremity kinematics and found that changing pelvic orientation alters hip kinematics (e.g., Heil et al., 1997; Savelberg et al., 2003). In addition, Savelberg et al. (2003) found that varying pelvic orientation altered ankle kinematics and the timing and magnitude of EMG for muscles crossing the hip and ankle joints. These studies suggest that both seat height and pelvic orientation

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have the potential to influence muscle power generation, and ultimately cycling performance, by altering lower extremity kinematics.

Of the three variables associated with seat configuration, seat tube angle (STA) varies the most across riding disciplines. For example, triathletes often prefer a STA that is more vertical (i.e., the seat is more forward relative to the crank center), while road racers often prefer a STA that positions the seat farther back relative to the crank (Garside & Doran, 2000; Heil et al., 1995). However, how STA influences overall muscle power output is not clear. One challenge with testing the influence of seat configuration on power output is the difficulty in isolating the effects of specific variables from each other as well as from the confounding effect of rider adaptation during the experimental testing. For example, Umberger et al. (1998) investigated the effect of STA on maximal power generation, but the experimental set-up did not control for pelvic orientation, which resulted in a systematic change in hip angle that could be a confounding factor in their study.

An alternative approach is to use theoretical modeling where the influence of specific variables can be carefully isolated. Gonzalez and Hull (1989) performed a multivariate optimization that included seat height and STA to identify the configuration that minimized a joint moment-based cost function during submaximal pedaling. However, joint moment–based cost functions do not include intrinsic muscle properties that have the potential to greatly influence muscle power output. Yoshihuku and Herzog (1996) developed a theoretical model with muscle actuators governed by intrinsic muscle properties to investigate the influence of pelvic orientation and seat height on maximal muscle power. However, they did not investigate the influence of STA on crank power. The goals of the current study were to build upon these previous experimental and modeling studies by using a muscle-actuated forward dynamics simulation of pedaling to: 1) identify the overall optimal seat configuration that produces maximum crank power, and 2) systematically vary seat tube angle to assess how it influences maximum crank power.

Methods

Overview

A musculoskeletal model (Neptune & Hull, 1998; Rankin & Neptune, 2008) and forward dynamics simulation were used within a dynamic optimization framework to identify the muscle excitation patterns and seat configuration (i.e., seat height, STA and pelvic orientation) that maximizes average crank power over a complete pedaling cycle at 90 rpm. To assess the influence of STA on maximum crank power, STA was then systematically varied over a wide range of values. At each STA, the muscle excitation patterns, seat height and pelvic orientation were optimized to assure that optimal values were used at each STA. The musculoskeletal model and optimization framework are described in detail below.

Musculoskeletal Model

The musculoskeletal model was developed using SIMM (Musculographics, Inc.) and consisted of nine segments including a pelvis, two legs and a crank and pedal system (Figure 1). Each leg consisted of thigh, shank, patella and foot segments. The crank segment was fixed to ground and allowed to rotate about its midpoint to represent standard 175 mm crank arms. Foot segments were fixed to the pedal to mimic standard pedals with clips and the pelvis segment was assumed to be fixed to the seat. The hip and knee joints were modeled as revolute joints while the patella joint was prescribed to follow a planar motion specified as a function of knee flexion angle to assure accurate moment arms for muscles crossing the knee joint (Yamaguchi & Zajac, 1989). The resulting model had three rotational degrees of freedom (crank and two pedal angles). Crank motion was prescribed to rotate at 90 rpm to simulate an isokinetic ergometer. Passive torques representing the forces applied by ligaments, passive tissues and joint structures were applied at the hip, knee and ankle joints (Davy & Audu, 1987). The dynamic equations of motion were generated using SD/FAST (Parametric Technology Corp.) and a forward dynamics simulation was produced using Dynamics Pipeline (Musculographics, Inc.).

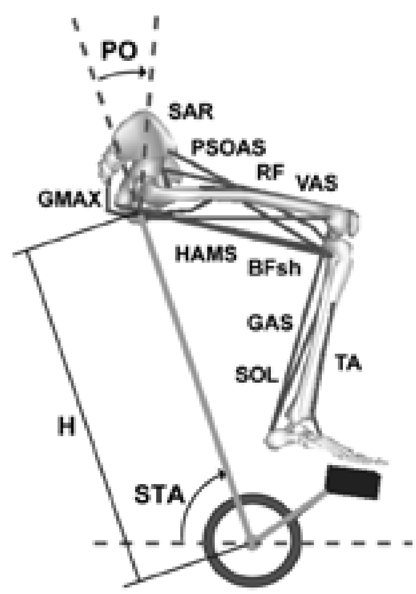

Figure 1 — Right leg of the bicycle–rider musculoskeletal model. The model has nine segments (2 legs, pelvis, crank and pedals) and 10 muscle groups defined as SAR (sartorius), PSOAS (iliacus, psoas), RF (rectus femoris), VAS (three component vastus), TA (tibialis anterior), SOL (soleus), GAS (gastrocnemius), BFsh (biceps femoris short head), HAMS (medial hamstrings, biceps femoris long head), and GMAX (gluteus maximus, adductor magnus). Seat configuration was defined by three parameters: seat height (H), seat tube angle (STA), and pelvic orientation (PO).

The major lower-extremity muscles of each leg were represented by fifteen musculotendon actuators that were combined into ten muscle groups based on anatomical classification (Figure 1), with muscles within each group receiving the same excitation pattern. Muscle force generation was modeled using a Hill-type muscle model that included passive and active force elements and governed by intrinsic muscle force-length-velocity relationships (Zajac, 1989). Muscle activation was coupled to the neural excitation using a first order differential equation to represent excitation-activation dynamics (Raasch et al., 1997) with activation and deactivation time constants of 20 and 30 ms, respectively. The excitation patterns for the two legs were considered symmetric and 180° out of phase.

Dynamic Optimization

A simulated annealing algorithm (Goffe et al., 1994) was used to perform the optimizations. The first optimization identified the optimal muscle excitation patterns and seat configuration (i.e., seat height, STA and pelvic orientation) that maximized average crank power over a complete pedaling cycle. To assess the sensitivity of STA on maximum crank power, a second set of optimizations were performed where the muscle excitation patterns, seat height and pelvic orientation were optimized as STA was systematically varied over a wide range of values (see Seat Configuration below) yielding a total of 21 additional optimizations.

Muscle Excitation Patterns.

The muscle excitation patterns were parameterized using a modified Gaussian pattern, defined by

$$u(t) = Ae^{-0.5\left|\left(\frac{t-\mu}{\sigma}\right)^{n}\right|} \tag{1}$$

where

$u(t)$ = muscle group excitation value at time t

A = magnitude scaling factor (range 0–1)

μ = center point of the excitation

σ = duration of the excitation

n = shape factor

This parameterization provided symmetric patterns about a central excitation point that could vary from a single block pattern to a smooth Gaussian shape. Since the optimal timing associated with each seat configuration was not known a priori, the excitation timing was unconstrained in all optimizations. The optimization identified the four parameters (A, μ, σ, n) associated with each of the 10 muscle groups (for a total of 40 excitation variables) that maximized average crank power.

Seat Configuration.

Seat configuration was defined using STA, seat height and pelvic orientation (Figure 1). STA was defined as the angle between the global horizontal axis and a line directed from the crank center to the hip joint center (seat tube) and allowed to vary between 65° and 110°. Pelvic orientation was defined as the angle between the seat tube and the vertical axis of the hip segment (i.e., a 0° angle represents a seat oriented perpendicular to the seat tube) and allowed to vary between –45° and 45°. Seat height was defined to be the distance between the crank center and the point at which the hip segment intercepts the seat tube and allowed to vary between 0.61 m and 0.81 m, which corresponds with pedal to seat distances of 82% and 109% greater trochanter height (i.e., the standing distance from the ground to the center of the greater trochanter). For the STA sensitivity analysis, STA was systematically incremented every 2.5° between 65° and 110°.

Analysis

A simulation of four consecutive crank cycles was generated during each optimization and data were analyzed during the fourth revolution to allow initial transient effects to dissipate and assure the simulation had reached steady state. To assure the optimization generated physiologically realistic muscle coordination patterns, the muscle excitation timing was compared with experimental EMG data from steady-state pedaling at 90 rpm (Neptune et al., 1997). For each optimization, the seat configuration, average crank power over the entire crank cycle, and the mean and range of the hip, knee, ankle, and pedal angles were determined.

Results

Maximum power of 981.3 W was generated at a seat height, STA and pelvic orientation of 0.76 m (or 102% greater trochanter height), 85.1° and 20.5°, respectively. As STA was systematically varied, maximum power varied across all solutions by at most 1% from the optimal value (Figure 2) with a consistent seat height and pelvic orientation (average [*SD*] of 0.76 [0.00] m and 20.5 [0.5] degrees, respectively). Mean and range of the hip, knee and ankle angles were also similar across STAs, with the largest variation occurring in the ankle angle (*SD* = 0.92°, Table 1). In contrast, the pedal angle systematically rotated in a clockwise direction as STA increased (Figure 3). The resulting excitation patterns were consistent with experimental EMG data and systematically shifted to later in the crank cycle as STA increased (Figure 4).

Table 1 Mean and range for the hip, knee, ankle and pedal angles (deg) across all STA optimizations

Angle	Mean (*SD*)	Range (*SD*)
Hip	125.17 (0.59)	54.73 (0.53)
Knee	101.19 (0.43)	94.09 (0.75)
Ankle	78.42 (0.66)	33.05 (0.92)
Pedal	–32.25 (15.91)	44.61 (0.49)

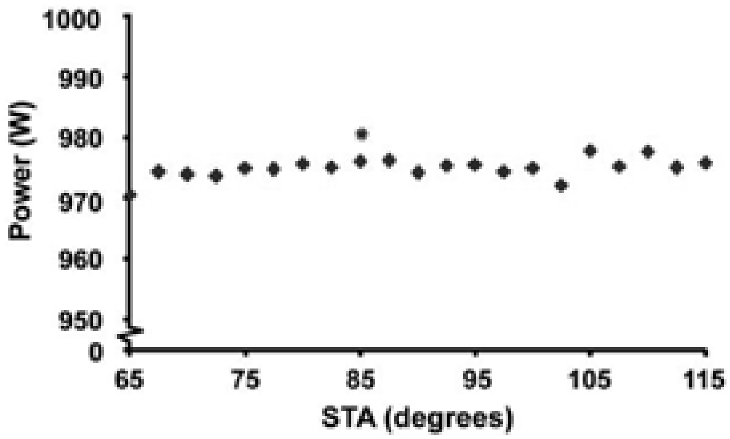

Figure 2 — Maximum average crank power for a single pedaling cycle versus STA. Diamonds represent the optimal power output for each of the 21 STA optimizations. The location of the global optimum is shown by an asterisk (*).

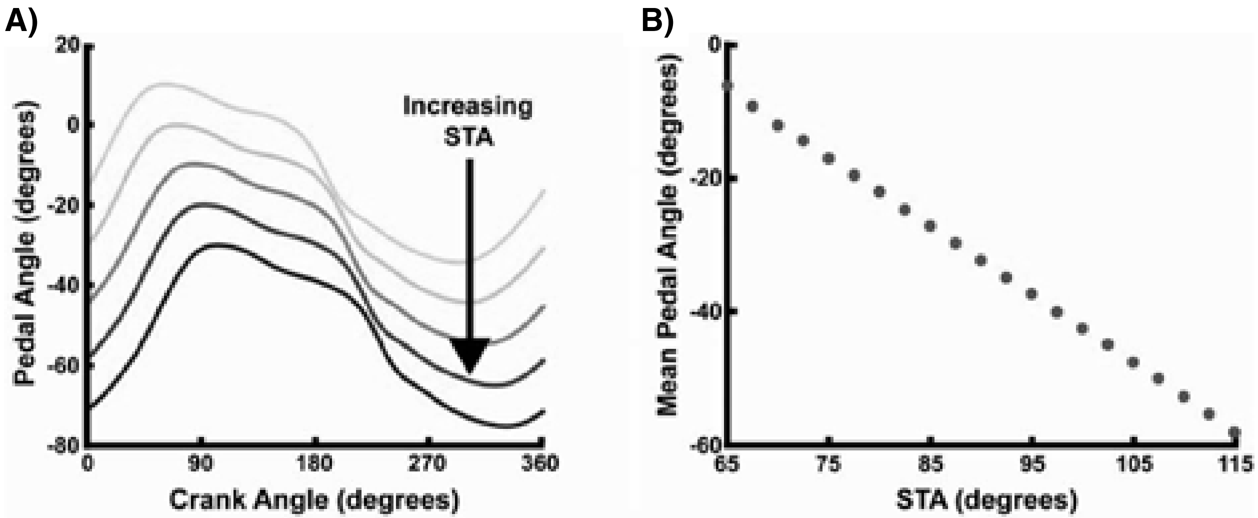

Figure 3 — A) Pedal angle trajectories for five different STAs. As STA increased, the pedal angle systematically rotated clockwise (i.e., more negative angles). B) Single cycle mean pedal angle (dots) versus STA angle for all optimizations performed.

Discussion

The optimization results showed that STA has little influence on maximum average crank power, with differences of 1% or less across the wide range of values (Figure 2). To obtain the similar power values across all STAs, each optimization produced a solution that resulted in joint kinematics nearly identical to the optimal solution (Table 1). In all cases, the kinematics were produced by combining near optimal seat heights and pelvic orientations with a systematic shift in the pedal angle as STA increased (Figure 3). This result was consistent with the findings of Browning et al. (1992) who observed a similar shift in pedal angle as they moved the seat forward when studying pedal forces in elite triathletes and competitive cyclists. Similarly, other studies have shown that variations in STA while fixing the seat height have little effect on the mean and range of knee and ankle angles (e.g., Heil et al., 1997; Reiser et al., 2002; Silder et al., 2009).

The generic musculoskeletal model used in this study generated an average maximum crank power of 981.3 W, which is similar to the optimal value of 1000 W reported by Yoshihuku and Herzog (1996) for their pedaling simulations incorporating experimentally determined optimal muscle fiber lengths. These crank power values were also consistent with the experimental results of Too (1991) and Umberger et al. (1998) that reported average power outputs between 821 W and 915 W for recreational cyclists. However, there were differences in both the optimal seat height (0.761 m, 102% greater trochanter height) and pelvic orientation (20.5°) between the current study and previous findings. Yoshihuku and Herzog (1996) found optimal seat heights and pelvic orientations ranging between 83–95% greater trochanter height and

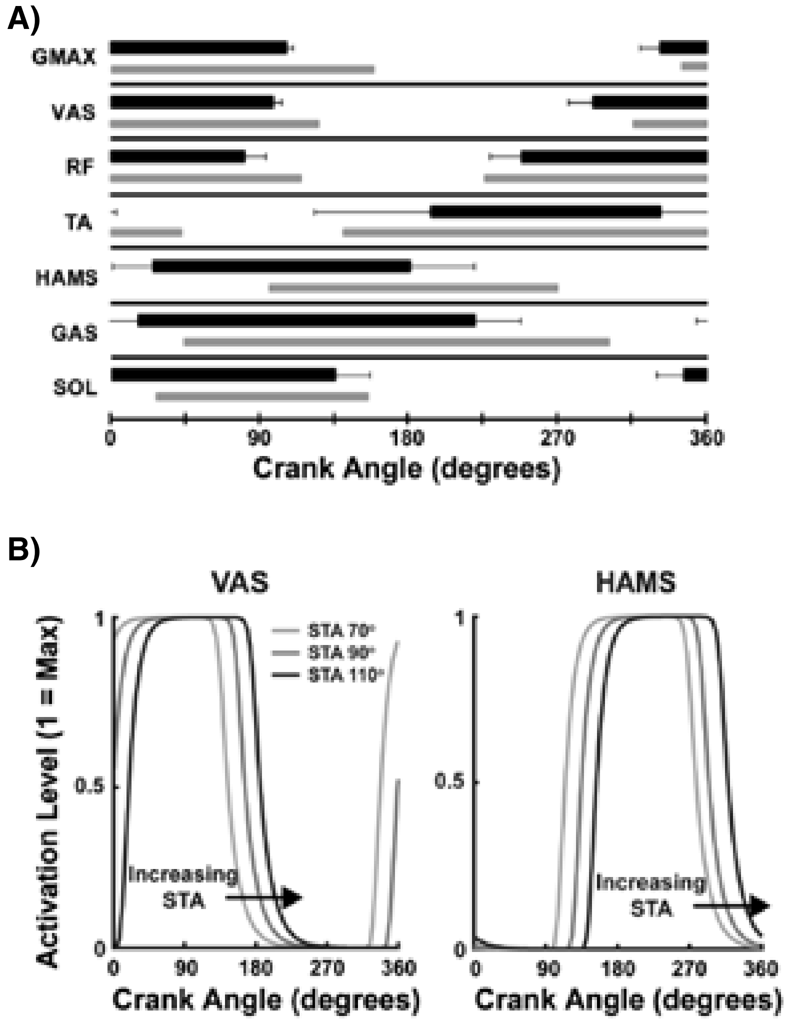

Figure 4 — A) Comparison of muscle excitation timing between a typical muscle excitation pattern produced from an optimization maximizing crank power (light bars, 75° STA) and experimental EMG data (± 1 *SD*) collected during a submaximal pedaling task at 90 rpm (dark bars, data taken from Neptune et al., 1997). B) Example phase shift in muscle timing for two muscle groups (VAS and HAMS). The excitation onset of all muscles increased systematically with increasing STA in the direction of the arrows. Relative timing between the different muscle groups did not change.

-6° to 6°, respectively, depending on the muscle length definition used. Umberger et al. (1998) reported a more flexed hip angle (mean of 91°), suggesting that a larger pelvic orientation (> 20°) is optimum. The disparities between the present findings and those of Yoshihuku and Herzog (1996) are most likely due to differences in muscle architecture (e.g., lines of action, muscle fiber orientation), pedaling rate (90 RPM vs. >140 RPM) and the absence of an ankle joint in their model. However, why our results differ from Umberger et al. (1998) is not clear, but may be due to the noncyclist population or non-steady-state pedaling protocol (15 s, maximal effort cycling) used in their study. However, it is possible that power output is relatively insensitive to pelvic orientation. To assess this possibility, a post hoc analysis of the influence of pelvic orientation on maximum crank power was performed. Dynamic optimization was used to maximize crank power at pelvic orientation angles ±10° from the optimal value and reductions in power output were found to be less than 3% of the optimal average crank power. Thus, differences between studies are most likely due to the insensitivity of pelvic orientation to power generation.

An analysis of the simulation muscle fiber lengths and velocities showed that the optimal joint kinematics corresponded to favorable operating conditions for muscle power generation from the hip and knee extensors VAS and GMAX (Figure 5), which are the primary power producing muscles in cycling (e.g., Neptune et al., 2000; Raasch et al., 1997). During active force generation, the average fiber length and velocity of these muscles were near the optimal values for power generation, resulting in increased crank power. To gain further insight into how changes in seat height influences muscle power output in light of the force-length-velocity relationships, two additional post hoc optimizations were performed that maximized crank power at fixed seat heights above and below (±4 cm) the optimal height. In both cases, average crank power decreased from the optimal value, with a larger reduction in power occurring at the higher seat value (939.3 W (–4 cm) and 820.7 W (+4 cm) vs. 981.3 W (optimal)). Examination of the VAS and GMAX muscle fiber lengths showed that the average VAS fiber length during active power generation moved away from the optimal value (normalized values of 0.935 [–4 cm] and 1.043 [+4 cm] vs. 0.995 [optimal]), while average GMAX fiber length either moved away from optimum (–4 cm, 1.089 vs. 1.064) or was similar to the optimal solution (+4 cm, 1.055 vs. 1.064; Figure 5). Fiber velocities for both VAS and GMAX systematically increased with higher seat heights (Figure 5). The change in VAS fiber lengths is attributed to a deviation in the mean knee angle from the optimal value (112.44° and 92.25° vs. 101.70°). Thus, seat height can have a significant influence on muscle power generation by causing muscles to operate in nonoptimal regions of the force-length relationship.

The optimal seat height of 0.76 m corresponds to 102% of greater trochanter height and an average knee flexion angle of 101.7° (min = 59.6°, max = 153.6°). These values are consistent with previous studies investigating relationships between seat height, joint kinematics, crank power and metabolic cost. Hamley and Thomas (1967) estimated that the optimal seat height for maximizing power output occurs near 100% trochanter height. Similarly, both Nordeen-Snyder (1977) and Price and Donne (1997) found that a seat height equal to 100% trochanter height minimized metabolic cost during steady-state submaximal pedaling. Nordeen-Snyder (1977) also reported an optimal average knee flexion angle of 101.5°, which is similar to the optimal value observed in the current study.

The excitation patterns were similar across STAs, although there was a systematic shift in the timing similar to the shift in pedal angle (Figure 4B). This systematic shift allowed muscles to remain active during the optimal joint configurations for generating muscle power. There were minimal changes in excitation magnitude, which was not consistent with Ricard et al. (2006), who observed a decrease in biceps femoris (BF) activity with increasing STA during Wingate tests performed by experienced triathletes ($n = 12$) . Differences between studies are most likely due to the different pedaling tasks studied, as the Wingate test is a non-steady-state pedaling activity that may elicit different muscle recruitment patterns.

Although the simulation results showed that there are a wide range of seat tube angles that produce similar values of maximum crank power, other factors not considered in this study may have a large influence on cycling performance. The most significant is the effect of riding posture on aerodynamic drag (e.g., Davies, 1980; Garcia-Lopez et al., 2008; Martin et al., 2007). In competitive cycling, a forward aerodynamic position is used to decrease the rider's projected frontal area, which greatly reduces the aerodynamic drag (e.g., Garcia-Lopez et al., 2008; Martin et al., 1998). However, such forward positions may create suboptimal hip angles that decrease the maximum power that can be delivered to the crank. For example, Gnehm et al. (1997) estimated in a group of 14 elite cyclists using an aerodynamic position that maximal crank power was reduced by 9 W as a result of nonoptimal hip angles. However, they also showed that the aerodynamic position would improve overall race performance by reducing power requirements by approximately 100 W when cycling at speeds ≥ 40 kph due to the decrease in aerodynamic drag.

The simulation results showed that seat height has a greater influence on power output than STA and pelvic orientation. However, the optimal seat height may be different for each rider due to individual differences in anthropometrics, muscle architecture and other

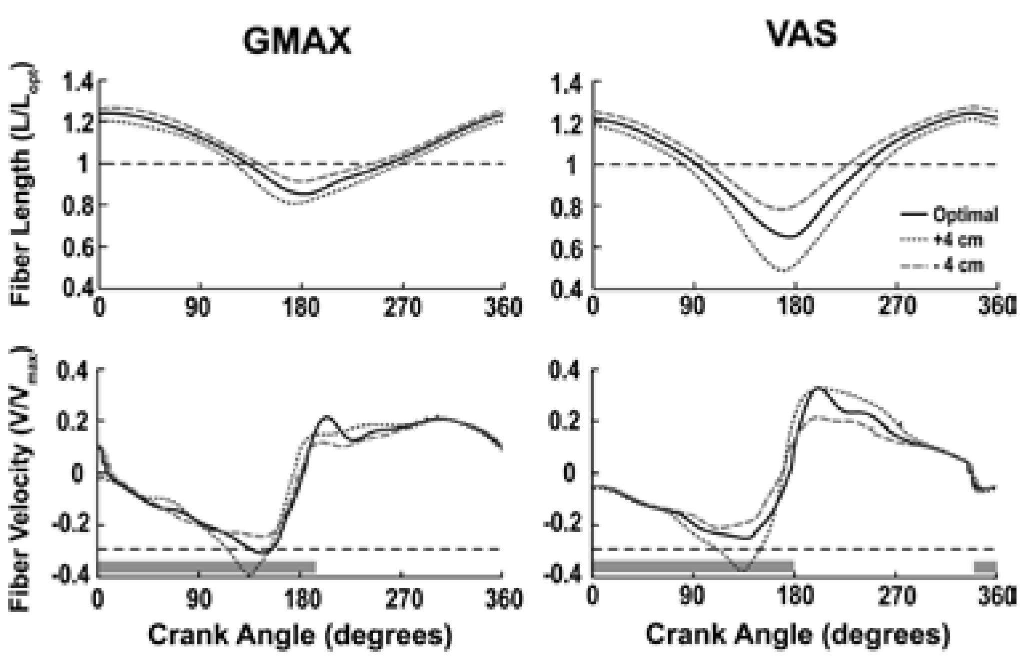

Figure 5 — Normalized fiber lengths and velocities from VAS and GMAX for a single pedaling cycle during the optimal solution (solid line) and the perturbed seat heights (+4 cm, dotted; –4 cm, dashed). Gray bars represent regions during which the muscle is actively producing force. Horizontal dashed lines indicate the optimal fiber length and velocity for maximal power generation.

neuromuscular parameters (e.g., femur length, muscle origin and insertion points, muscle fiber orientation). Gonzalez and Hull (1989) used a cycling model with a fixed handlebar to investigate the influence of subject anthropometrics on seat height and STA that minimized joint moments during submaximal pedaling. They showed that subject anthropometrics greatly influenced both seat height and STA, suggesting that individual rider anthropometrics and musculoskeletal architecture will affect the optimal joint angles and corresponding seat configuration that maximizes crank power. In addition, previous studies investigating muscle architecture of competitive runners, speed skaters, and cyclists have shown that individual muscles can adapt over time to increase the efficiency of performing specific tasks (e.g., Herzog, 2000; Herzog et al., 1991; Savelberg & Meijer, 2003). Thus, even if nonoptimal seat configurations are adopted, long-term adaptation of muscle architecture can improve muscle force and power output.

Conclusion

The simulation results showed there exists an optimal seat height, STA and pelvic orientation that maximizes crank power. However, maximum power is most sensitive to seat height. Similar power output levels were observed across all STAs, which were achieved by systematically shifting the pedal angle with increases in STA to allow the hip, knee, and ankle joint kinematics to remain within the optimal range for muscle power generation based on the force-length-velocity relationships. Thus, there does not appear to be an advantage of one STA vs. another when maximizing crank power. However, adjusting the STA will affect riding posture and aerodynamic drag, which has been shown to greatly influence cycling performance. Therefore, modifying the STA may allow a rider to achieve a more optimal upper body posture that minimizes aerodynamic drag without greatly sacrificing the ability to generate maximal crank power, which will ultimately improve overall cycling performance.

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