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The Effect of Body Position/Configuration and Orientation on Power Output

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THE EFFECT OF BODY POSITION/CONFIGURATION AND ORIENTATION ON POWER OUTPUT

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Introduction

It is well documented that recumbent human power vehicles are more effective aerodynamically than the standard cycling position (Kyle 1974, 1982; Kyle & Caiozzo, 1986; Kyle, Crawford, & Nadeau, 1973, 1974; Whitt & Wilson, 1982). With speeds of some human powered vehicles exceeding 60 mph (96.6 km/hr) (Gross, Kyle, & Malewicki, 1983), it is obvious as to the importance of minimizing aerodynamic drag. But when the drag coefficient and effective frontal area have been reduced to 0.11 and 0.5 square feet, respectively, as in the Vector Single (compared to 1.1 and 6.0 square feet, respectively for a standard upright bicycle) (Gross et al., 1983), it is questionable as to (1) how much lower the aerodynamic drag can be reduced; and (2) how significant such changes would be.

The design of human powered vehicles has focused exclusively on the aerodynamic properties of the vehicle with the cyclist. To further improve performance, it becomes necessary to focus on some aspect other than the aerodynamic properties. The most logical area to explore would be the human engine that powers the vehicle. But, how efficient or effective is a cyclist when pedaling in a supine, semi-supine, semi-prone, or prone position? What is the most effective body configuration (hip, knee, ankle angles) to maximize force and power production and to optimize tension-length, force-velocity-power interaction of multijoint muscles? Will changes in body orientation affect power production by altering the leg position with respect to the gravity line, thus affecting body weight contribution to the pedals? It should be noted that the most effective position, configuration, and orientation may not necessarily minimize aerodynamic drag. The optimum seating position may involve some compromise between minimizing aerodynamic drag and maximizing cycling effectiveness.

To date, there are very few scientific investigations that have systematically examined the body positions, configurations, and orientations a cyclist should adopt to maximize power production and cycling performance. There has not been any logical rationale or empirical evidence as to why one position, configuration, or orientation should result in greater power production and cycling performance than another or why a cyclist should be placed in recumbent-type positions except to minimize aerodynamic drag. This is an area not only largely unexplored, but also one predominantly neglected and in great need of research if the limits of performance in human powered vehicles are to be achieved.

Kinesiologists, unlike engineers, have always examined cycling performance based on a human factors perspective. But, these investigations have always been based on the constraints imposed by the structure of a conventional bicycle. These investigations have included the effects on cycling performance with changes in seat height, crank arm length, pedaling frequencies, workloads, total work output, etc. Therefore, a gap exist between research in the various disciplines. To maximize/optimize cycling performance in human powered vehicles requires a bridging of this gap through interdisciplinary research.

The purpose of these investigations were to determine the effect of systematic changes in: (1) body position/configuration (seat tube angle/hip angles); and (2) body orientation (trunk angle with respect to the ground) on cycling performance as defined by power output.

Experiment 1

Body position is defined by the location of the cyclist's hip relative to the pedal axle of the bicycle and is determined by the angle of the bicycle seat tube and a vertical line (perpendicular to the ground) passing through the pedal axle. Body con-

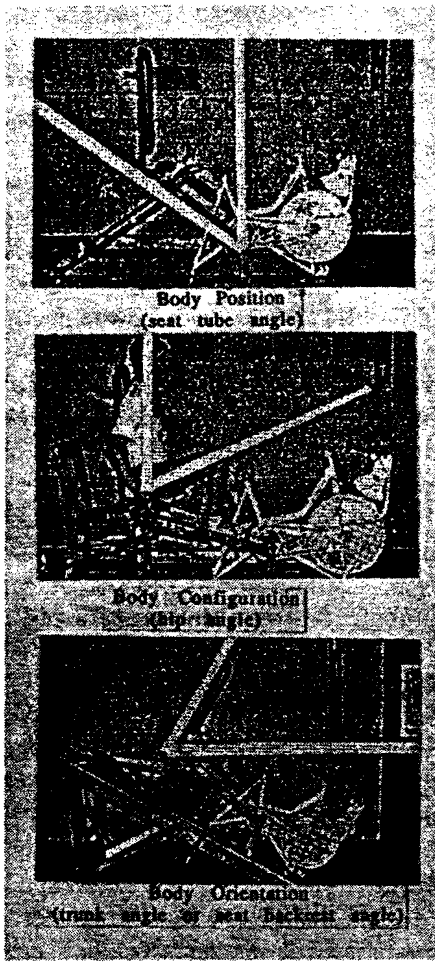


Figure 1. Definition of Body Position, Configuration and Orientation

Figure 2. Body Positions/Configurations

figuration is defined by the angles of the different body segments (hip, knee, ankle) relative to each other. Body orientation is defined by the angle of the cyclist's trunk relative to the ground (Figure 1).

Methods

Fourteen male recreational cyclists 21-32 years of age (mean = 26.2 years) volunteered to participate in this study. Their average height and mass were 1.75 m (SD = 0.04) and 69.8 kg (SD = 6.2), respectively. All subjects were tested in each of four different body positions (25, 50, 75, and 100 degrees) as defined by the angle formed between the bicycle seat-tube and a vertical line (Figure 2). To accomplish this, an apparatus was constructed onto a bicycle ergometer. By rotating the seat to maintain a backrest perpendicular to the ground, a systematic decrease in hip angle from the 25 to 100 degree positions was induced. For each position, the seat to pedal distance was adjusted to remain 100% (to within 3/4 inch or 1.905 cm) of the total leg length, as measured from the greater trochanter of the femur of the right leg to the ground. In each position, the minimum and maximum hip, knee, and ankle angles were obtained for one complete pedal revolution (Table 1). The body configuration was defined by the average hip angle for one complete pedal revolution (average differences between minimum and maximum hip

Table 1. Hip knee and ankle angles at four seat-tube angles

		Seat-tube Angle (deg)			
		25	50	75	100
Hip (deg)					
Minimum	M	93.70	79.70	54.40	37.90
	SD	4.21	5.31	6.92	5.40
Maximum	M	135.30	120.40	96.70	79.80
	SD	4.65	6.90	4.81	3.53
Average	M	114.00	100.10	75.50	58.90
	SD	3.53	5.01	3.86	3.98
Range	M	41.90	40.70	42.40	42.60
	SD	6.90	7.17	9.09	5.77
Knee (deg)					
Minimum	M	62.90	63.20	64.50	65.10
	SD	4.85	3.07	3.61	5.31
Maximum	M	133.60	136.80	142.60	138.10
	SD	6.64	6.44	7.11	11.90
Average	M	98.20	100.00	103.60	101.60
	SD	5.36	4.45	4.38	8.21
Range	M	73.50	73.60	77.40	73.00
	SD	11.93	4.72	7.19	8.51
Ankle (deg)					
Minimum	M	83.40	81.90	83.40	78.80
	SD	6.20	8.33	11.06	10.78
Maximum	M	101.70	93.30	102.20	101.40
	SD	8.77	7.00	6.48	7.68
Average	M	92.50	89.60	92.80	90.10
	SD	6.65	6.57	7.19	7.93
Range	M	18.40	15.40	18.10	23.00
	SD	7.32	8.00	11.21	10.06

angle). All subjects were tested in each of the four body positions, according to a randomly determined sequence, and a minimum of 24 hours rest between sessions.

The Wingate Anaerobic Cycling Test (Lamb, 1984), an all out 30 second power test was used on a Monark Cycle ergometer with a resistance of 85 gm/kg of the subject's body mass (5.0 joules/pedal rev/kg BM). During the test, each subject was strapped to the seat-backrest at the waist and hips, pedal toe-clips were worn, and a micro-switch on-line with a Technirite analog strip recorder was used to monitor ergometer flywheel revolutions. The recording paper had 10 squares/cm and the recorder speed was set at 25 mm/sec. The peak number of flywheel revolutions in any 5 second interval was used to determine peak power output and total number of flywheel revolution in the 30 second test was used to determine anaerobic capacity. Because the pedal resistance was determined according to each subject's body mass, the recorded number of flywheel revolutions represented peak power output normalized according to body mass.

This relative peak power was calculated by the following equation: Power (kgm/min) = distance traveled by one flywheel revolution (6 meters per revolution) x flywheel resistance (kg) x pedaling frequency (revolutions per minute). Because one watt equals 6.12 kpm/min (Astrand & Rodahl, 1977), the resulting power in kgm/min divided by 6.12 kpm/min converted the units of power to watts (or joules/second). Absolute peak power was then determined by the product of relative peak power and body mass. Anaerobic capacity was determined by the average number of flywheel revolutions for the six periods of successive 5 seconds in the 30 second test. This mean relative power represents the maximal capacity to produce energy anaerobically (Lamb, 1984). The total anaerobic capacity was then calculated by the product of the mean relative power and body mass.

Results

From Table 1, a systematic decrease in the minimum, maximum, and average hip angles with changes in body position from the 25 to 100 degree position can be observed. Similar hip angle range of motions as well as mean knee angles with changes in body positions are evident. Since the seat-to-pedal distance was controlled for, differences in cycling performance can be attributed to changes in body configuration (hip angle).

The mean peak power output (PP), anaerobic capacity (AC), power output and anaerobic capacity relative to each subject's body mass (PP/kg BM and AC/kg BM, respectively), and the fatigue index (FI) for the different body positions are presented in Table 2.

A repeated measures MANOVA revealed significant differences ($p < .01$) with changes in hip position in: PP with $F(3, 39) = 13.6$, AC with $F(3, 39) = 15.85$, PP/kg BM with $F(3, 39) = 13.39$, and AC/kg BM with $F(3, 39) = 15.36$. Post-hoc tests (Dunnett)

Table 2. Mean values for absolute and relative peak power output and anaerobic capacity, with the fatigue index for four seat-tube angles and the corresponding hip angles

Seat-tube Angle (deg)		25	50	75	100
Hip Angle (deg)		114.0	100.1	75.5	58.9
PP (W)	M	739.20	800.10	821.20	763.10
	SD	134.20	126.80	122.90	111.90
AC (W)	M	526.30	569.80	579.70	547.20
	SD	82.40	82.80	75.10	74.20
PP/kg BM	M	10.55	11.43	11.73	10.91
(W/kg BM)	SD	1.38	1.17	1.03	1.04
AC/kg BM	M	7.53	8.14	8.29	7.84
(W/kg BM)	SD	0.85	0.66	0.61	0.73
FI (%)	M	49.40	48.80	49.60	47.90
	SD	9.63	4.23	7.16	5.54

were used to compare the 75 degree body position (also corresponding to the 75 degree hip angle body configuration) with each of the other 3 positions. It was found that the PP, AC, PP/kg BM, and AC/kg BM in the 75 degree position/configuration was significantly greater than in the 25 and 100 degree positions (114 and 59 degree hip angle body configuration, respectively) ($p < .01$); but not significantly different from those in the 50 degree position (100 degree hip angle body configuration). Based on trend analysis, a quadratic function ($p < .01$) was found to best describe the change in PP, AC, PP/kg BM, and AC/kg BM with changes in hip angles from 114 to 59 degrees (Figure 3).

Discussion

The 75 degree body position/configuration that resulted in the largest performance values for power output and anaerobic capacity is identical to the seat-tube angle and hip angle reported in the literature that maximized aerobic work (Too, 1988, 1990a, b). The results of this investigation also indicate a significant curvilinear trend in PP and AC with changes in body position/configuration. This trend may be attributed to differences in minimum and maximum hip angle values with changes in body position. Although there is a similar hip angle range of motion with changing body position, the differences in minimum and maximum hip angle values would suggest that, the development of force and production of power vary at different hip angles with changes in body position. This is an explanation for differences in PP and AC with changes in body position/configuration. This would also suggest some body position/configuration, with an upright trunk orientation, which maximizes PP, AC, PP/kg BM, and AC/kg BM.

Verbal feedback from the subjects appear to support this curvilinear trend and performance differences. In the 25 degree body position, subjects indicated that muscle fatigue was greatest in the quadriceps region, whereas, it was greatest and localized in the gluteal area for the 100 degree body position. However, in the 75 degree body position, subjects reported muscular fatigue to be more generalized throughout the lower extremities. This would suggest that the 75 degree body position and other similar body positions allow for a more equitable distribution of load over the various muscle groups involved and may minimize local fatigue.

Conclusion

Cycling performance as measured by peak power output and capacity in the 75 degree seat-tube angle body position (75.5 degree hip angle body configuration) was significantly greater ($p < .01$) than that in the 25 or 100 degree seat-tube angle body position(114 and 58.9 degree hip angle, body configuration, respectively). A second order function (inverted U-curve) best describe the trend in power output and capacity with changes in body position/configuration ($p < .01$). It was concluded that an optimal cycling body position/configuration exist which maximizes power output and capacity in cycling performance.

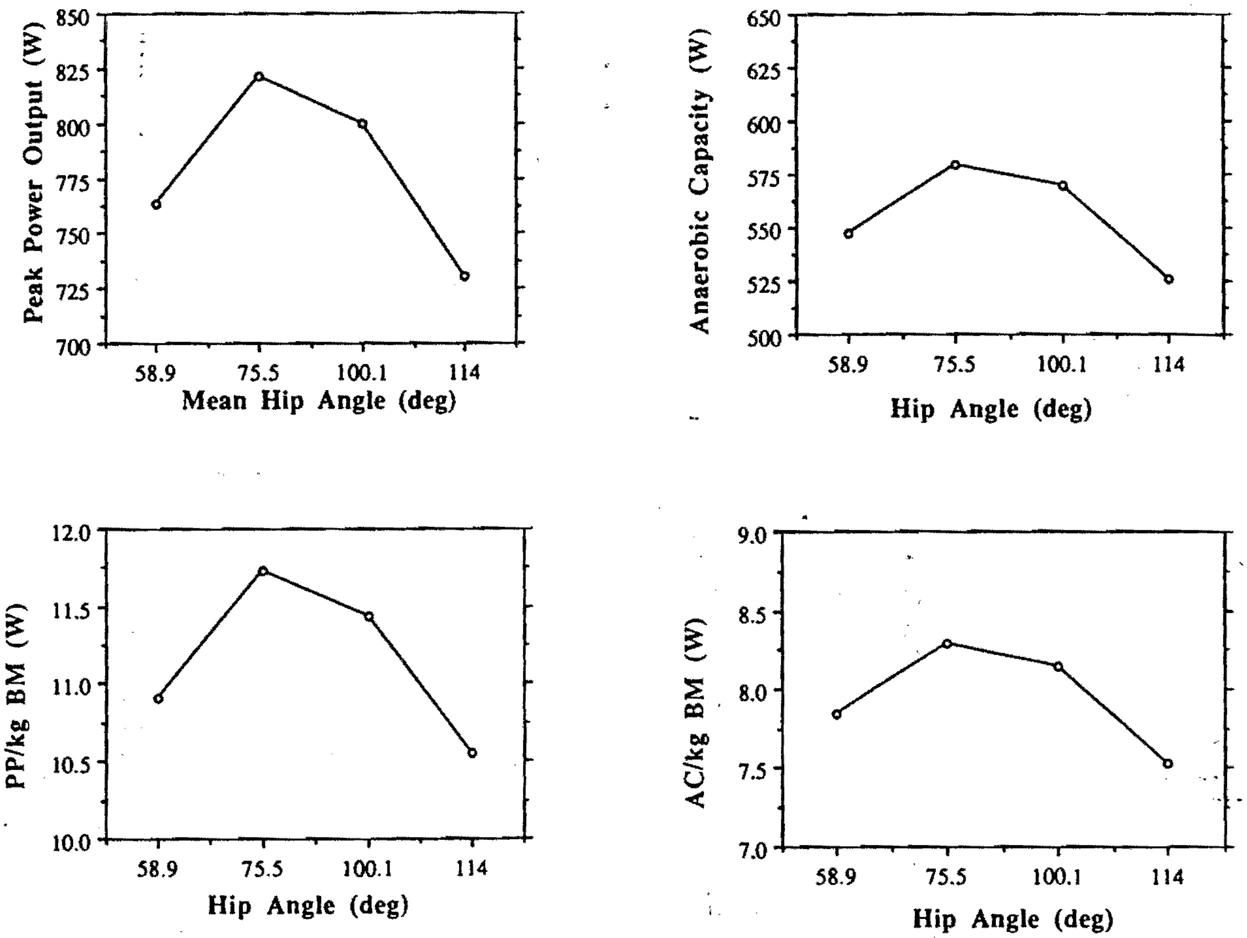
Experiment 2

Based on the results of experiment 1, the purpose of this investigation was to determine the effect of systematic changes in body orientation on power output, while controlling for body position and configuration.

Methods

Sixteen male recreational cyclists age 20-36 years of age (mean = 26.5 years) volunteered to participate in this study. Their average height and

FIGURE 3



mass were 1.76 m (SD = 0.08) and 77.1 kg (SD = 9.5), respectively. Each subject was tested in 3 different body orientation (60, 90, and 120 degrees), as defined by the angle of the cyclist's trunk relative to the ground (Figure 4). A 75 degree body position (seat tube angle) was used and a platform constructed to allowed the cycling apparatus to be rotated 30 degrees forward or backward. The hip, knee and ankle angles were controlled for in all 3 orientations. For each orientation, the seat to pedal distance was adjusted to remain 100% (to within 3/4 inch or 1.905 cm) of the total leg length, as measured from the greater trochanter of the femur of the right leg to the ground. All subjects were tested in each of the 3 body orientations (BO) according to a randomly determined sequence, with a minimum of 24 hours rest between sessions.

The test protocol used was identical to that in experiment 1. The Wingate Anaerobic Cycling Test was used on a Monark Cycle ergometer with a resistance of 85 gm/kg of the subjects' body mass (5.0 joules/pedal rev/kg BM). During the test, each subject was strapped to the seat-backrest at the waist and hips, pedal toe-clips were worn, and a micro-switch on-line with a Macpaq analog to digital converter interfaced to a Macintosh SE microcomputer was used to monitor and record ergometer pedal revolutions. Pedal revolution data was collected with a computer program (Pacqmanager) at a rate of 200 samples/second.

Relative peak power output was determined as the largest number (or fraction) of pedal revolutions over any successive 5 second interval. Relative anaerobic capacity was determined from the 30 second test as the average number of pedal revolutions for the six periods of successive 5 seconds in the 30 second test. Absolute peak power was then determined by the product of relative peak power and body mass. Absolute anaerobic capacity was determined similarly.

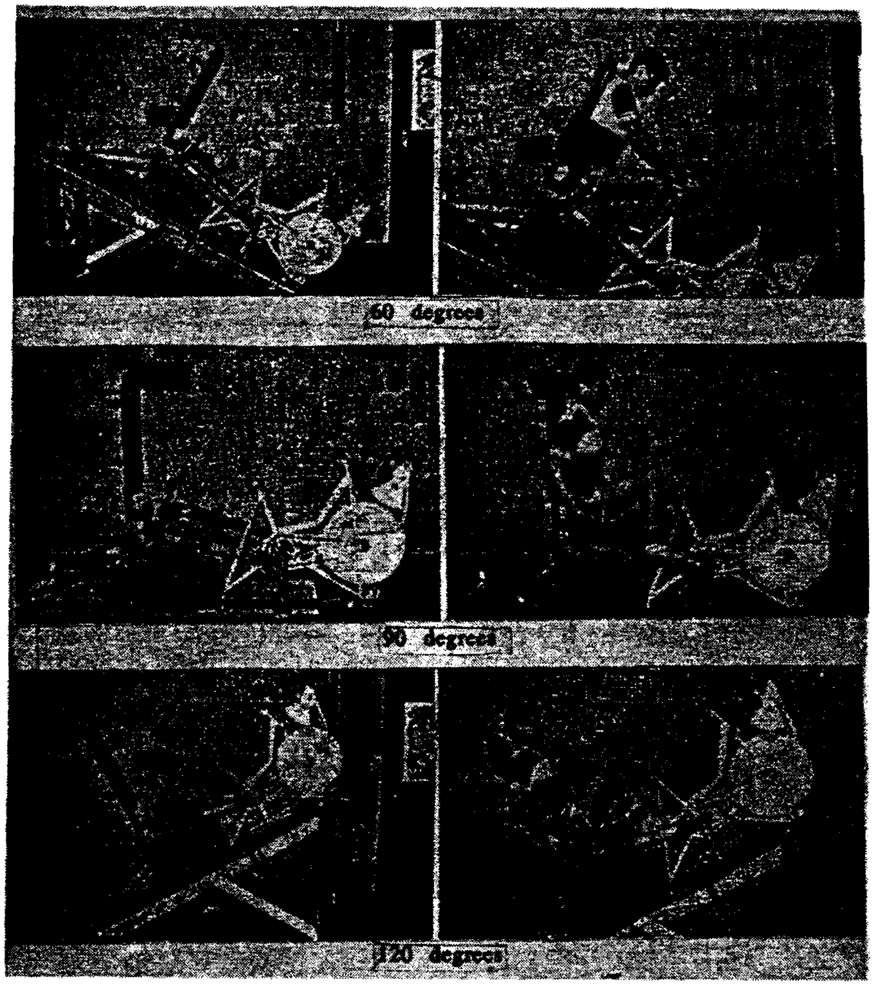


Figure 4. Body Orientations

Results

No significant differences in hip, knee, and ankle angles were found across the three body orientations. This would indicate that any differences in cycling performance would be attributed to changes in trunk orientation and not to alterations in body configuration (hip, knee, and ankle angles).

The mean peak power output (PP), anaerobic capacity (AC), power output and anaerobic capacity relative to each subject's body mass (PP/kg BM and AC/kg BM, respectively), and the fatigue index (FI) for the different body orientations are presented in Table 3.

Repeated measures ANOVAs revealed significant differences ($p < .01$) with changes in body orientation in: PP with $F(2, 32) = 14.1$, AC with $F(2, 32) = 7.57$, PP/kg BM with $F(2, 32) = 7.95$, and AC/kg BM with $F(2, 32) = 5.18$. Post-hoc tests (Fisher PLSD) were used to determine where the significant differences occurred. It was found that the PP and PP/kg BM was significantly greater at the 60 and 90 degree body orientation when compared to the 120 degree orientation ($p < .05$); but not significantly different from each other. It was also determined that AC and AC/kg BM in the 90 degree body orientation was significantly greater than that in the 120 degree orientation ($p < .05$); but not significantly different from that in the 60 degree orientation. No differences were found in AC and AC/kg BM between the 60 and 120 degree body orientation.

Discussion

There are often varying arguments as to the effectiveness of cycling in a semi-supine position (e.g., 120 degree body orientation) versus that in a semi-prone position (e.g., 60 degree body orientation). It is often argued that a semi-supine position is more comfortable and more effective because it would allow the cyclist to use the seat backrest to apply a force on the pedals which is greater than body weight. On the other hand, it is often argued that a semi-prone position is a more effective position to cycle in because it will position the lower limbs in an orientation that would maximize the contribution of the body weight to the pedals (although the backrest may not be used, or there may not be a backrest to push against).

The results of this investigation would suggest that perhaps neither the semi-supine or semi-prone position is more effective than the other (at least not in regard to anaerobic capacity). The advantage of a semi-supine position, allowing a cyclist to more effectively use the backrest, may be negated by having to overcome the weight of the lower limbs while pedaling as well as having to overcome the resistance of the vehicle.

A more effective cycling position may be that

Table 3. Mean absolute and relative peak power output and anaerobic capacity, with fatigue index at three body orientation

		Body Orientation (deg) 60	90	120
PP (W)	M	934.50	944.60	894.60
	SD	137.00	128.10	105.60
AC (W)	M	692.00	712.20	662.10
	SD	87.60	101.10	66.00
PP/kg BM	M	12.14	12.29	11.68
(W/kg BM)	SD	1.13	1.19	1.25
AC/kg BM	M	9.00	9.27	8.73
(W/kg BM)	SD	0.65	0.89	0.97
FI (%)	M	46.00	44.30	46.10
	SD	6.91	4.27	7.31

in a neutral position (e.g., 90 body orientation) with a backrest to push against, but without having to overcome the weight of the lower limbs. But how this would affect the cross-sectional area of the vehicle and cyclist, and the resulting aerodynamic drag is unknown. To select a body position/configuration and orientation that would maximize power output, minimize aerodynamic drag and optimize cycling performance may require some compromise in all areas of concern; and will definitely require further investigations

Conclusion

Cycling performance as measured by peak power output in the 60 and 90 degree body orientation was significantly greater than that in the 120 degree body orientation ($p < .05$); and (2) anaerobic capacity in the 90 degree body orientation was significantly greater than that in the 120 degree body orientation ($p < .05$). No significant differences were found in peak power output and capacity between the 60 and 90 degree body orientation. It was concluded that an optimal cycling body orientation exist which maximizes power output and capacity.

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