

The influence of pedaling rate on bilateral asymmetry in cycling

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Abstract

The objectives of this study were to (1) determine whether bilateral asymmetry in cycling changed systematically with pedaling rate, (2) determine whether the dominant leg as identified by kicking contributed more to average power over a crank cycle than the other leg, and (3) determine whether the dominant leg asymmetry changed systematically with pedaling rate. To achieve these objectives, data were collected from 11 subjects who pedaled at five different pedaling rates ranging from 60 to 120 rpm at a constant workrate of 260 W. Bilateral pedal dynamometers measured two orthogonal force components in the plane of the bicycle. From these measurements, asymmetry was quantified by three dependent variables, the percent differences in average positive power (%AP), average negative power (%AN), and average crank power (%AC). Differences were taken for two cases — with respect to the leg generating the greater total average for each power quantity at 60 rpm disregarding the measure of dominance, and with respect to the dominant leg as determined by kicking. Simple linear regression analyses were performed on these quantities both for the subject sample and for individual subjects. For the subject sample, only the percent difference in average negative power exhibited a significant linear relationship with pedaling rate; as pedaling rate increased, the asymmetry decreased. Although the kicking dominant leg contributed significantly greater average crank power than the non-dominant leg for the subject sample, the non-dominant leg contributed significantly greater average positive power and average negative power than the dominant leg. However, no significant linear relationships for any of these three quantities with pedaling rate were evident for the subject sample because of high variability in asymmetry among the subjects. For example, significant linear relationships existed between pedaling rates and percent difference in total average power per leg for only four of the 11 subjects and the nature of these relationships was different (e.g. positive versus negative slopes). It was concluded that pedaling asymmetry is highly variable among subjects and that individual subjects may exhibit different systematic changes in asymmetry with pedaling rate depending on the quantity of interest. © 1999 Elsevier Science Ltd. All rights reserved.

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1. Introduction

The analysis of pedaling asymmetry as a function of pedaling rate is important for a variety of reasons. One reason concerns the development of overuse knee injuries which plague both recreational and competitive cyclists (e.g. Holmes et al., 1991). Identifying the pedaling rate which more evenly distributes pedaling forces to both legs would allow cyclists to select this pedaling rate,

reduce the knee loads transmitted by the more dominant leg, and thus reduce the risk of overuse injuries. Another reason to study asymmetry is to identify the less dominant leg to improve training programs. Because leg dominance may change with pedaling rate, the training program may need to be pedaling rate specific to develop the less dominant leg. Additionally, quantifying pedaling asymmetry across different pedaling rates would provide insight into motor control principles for left/right coordination which have been investigated in previous human locomotion studies (e.g. Arsenaault et al., 1986). Finally, such analysis would be useful in both guiding the development of mathematical models which simulate cycling biomechanics over a range of pedaling rates and providing experimental data for validating such models (e.g. Neptune and Hull, 1998).

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Although a number of previous studies has examined bilateral pedaling mechanics (Cavanagh et al., 1974; Daly and Cavanagh, 1976; Hoes et al., 1968; LaFortune et al., 1989; McCartney et al., 1983; Patterson and Moreno, 1990; Sanderson, 1991; Sargeant and Davies, 1977; Sirin et al., 1989), only the two early papers by Cavanagh and co-workers systematically examined asymmetry across different pedaling rates. In the later of the two papers, asymmetry was examined using cranks instrumented to measure torque of cyclists riding a stationary ergometer at pedaling rates of 40, 70, and 100 rpm. Using footwear which consisted of soft-soled shoes resting on the pedal surfaces, the subjects clearly demonstrated significant effects with the speed of pedaling.

Although the paper by Daly and Cavanagh (1976) was useful in identifying a dependence of asymmetry on pedaling rate, the procedures used in the study limit its usefulness to address the reasons to study asymmetry mentioned above. One procedural limitation was that only the crank torque was measured and not the pedal load components. Since it is the pedal force components which dictate the intersegmental joint loads and hence muscle forces that produce the intersegmental moments, measurements of crank torque alone provide insufficient information to be useful either to study coordination or to develop mathematical models. Another limitation was that the shoe–pedal interface did not fix the shoe to the pedal. Since pedaling mechanics have been shown to be profoundly influenced by free versus fixed connections (Davis and Hull, 1981), and most if not all recreational and competitive cyclists currently use some type of fixed connection, the results are not applicable to the subject population of primary interest. Finally, although different pedaling rates were used in the experiments, the paper presented no quantitative results illustrating the dependence of asymmetry on pedaling rate.

Considering the limitations above, the general objective of the work reported in the present paper was to study the effect of pedaling rate on pedaling mechanics asymmetry using an experimental protocol that would yield results applicable to experienced recreational and competitive cyclists. To quantitatively investigate pedaling rate effects, three hypotheses were tested. The first hypothesis was that the asymmetry as measured by the difference in crank power-related quantities between the two legs changes systematically with pedaling rate. The second and third hypotheses were that the dominant leg as identified by kicking contributes more crank power than the other leg and that this contribution also changes systematically with pedaling rate. For all three hypotheses, the crank power-related quantities of interest were the average positive power, average negative power, and the total average power.

2. Methods

Kinetic and kinematic data were collected from 11 male competitive cyclists (avg. and S.D. of height = 1.79 ± 0.07 m; weight = 68.8 ± 7.6 kg; age = 22.2 ± 2.7 yr). Informed consent was obtained before the experiment. The subjects rode a conventional racing bicycle adjusted to match their own bicycle's geometry. The bicycle was mounted on an electronically braked Schwinn Velodyne ergometer that provided a constant workrate (i.e. average power) independent of pedaling rate. The protocol consisted of a 10-min warm-up period at a workrate of 120 W at 90 rpm. Then, each subject cycled at a workrate of 250 W at five different pedaling rates (60, 75, 90, 105 and 120 rpm) randomly assigned to control for possible interactions and fatigue. After a 3-min adaptation period, data collection was randomly initiated five times for a duration that captured five consecutive cycles each during the following 3-min. The subjects maintained the appropriate pedaling rate by observing a digital display indicating the current rate.

The intersegmental moments were computed using a standard inverse dynamics approach. The rider was modeled as a five-bar linkage in plane motion. The equations of motion for each link were solved using inverse dynamics, starting with the foot and proceeding through each link to the hip. The anthropometric estimates of each segment's mass and center of gravity were defined based on the work of Dempster (1955). Moments of inertia were computed by the data presented in Whittsett (1963) which were personalized to each subject based on the work of Dapena (1978).

The necessary kinematic data were recorded using a combination of video-based motion analysis and direct measurement. The intersegmental joint centers were measured using a high speed video system (Motion Analysis Corp., Santa Rosa, CA) with reflective markers located over the left and right anterior-superior iliac spine (ASIS), greater trochanter, lateral epicondyle, lateral malleolus and pedal spindle. The hip joint center was located relative to the marker over the ASIS based on the methodology presented in Neptune and Hull (1995). Collected at 60 Hz, the video data were filtered using a fourth-order zero-phase shift Butterworth low pass filter with a cutoff frequency of 9 Hz. All derivatives to determine coordinate velocity and acceleration were calculated by fitting a quintic spline (GCVSPL, Woltring, 1986) to the position data and differentiating the resulting equations.

The angular orientations of the crank arm and left and right pedals were measured with three optical encoders, and the pedal forces were measured with two pedal dynamometers described by Newmiller et al. (1988). The encoder and pedal force data were collected simultaneously with the video data at 100 Hz. The pedal force and encoder data were filtered using a fourth-order

zero-phase shift Butterworth low pass filter with a cutoff frequency of 20 Hz. The filtered data were linearly interpolated to correspond in time with the video coordinate data.

To quantify the power developed by each leg, the instantaneous power was computed as the product of the crank torque and crank angular velocity. For each leg, subject, and pedaling rate, the instantaneous powers from each crank cycle were then averaged. From these average cycles, the average positive power \bar{P}_{pos} , the average negative power \bar{P}_{neg} , and the total power \bar{P}_{leg} for each leg, subject and pedaling rate were computed.

Statistical analysis procedures were used to test the various hypotheses. To investigate whether the difference in power between the two legs changed systematically with pedaling rate, the statistical analysis consisted of simple linear regressions. Three separate analyses for the subject sample were performed on each of the three dependent variables. The dependent variables were the percent difference in average positive power (%AP), the percent difference in average negative power (%AN), and the percent difference in total average crank power (%AC) computed according to the following equations:

$$\%AP = \frac{\bar{P}_{\text{pos,high}} - \bar{P}_{\text{pos,low}}}{\bar{P}_{\text{pos,high}} + \bar{P}_{\text{pos,low}}} \quad (1)$$

$$\%AN = \frac{\bar{P}_{\text{neg,high}} - \bar{P}_{\text{neg,low}}}{\bar{P}_{\text{neg,high}} + \bar{P}_{\text{neg,low}}} \quad (2)$$

$$\%AC = \frac{\bar{P}_{\text{leg,high}} - \bar{P}_{\text{leg,low}}}{\bar{P}_{\text{leg,high}} + \bar{P}_{\text{leg,low}}} \quad (3)$$

One of the three separate regression analyses included all subjects in the sample. To provide a consistent reference for computing the differences indicated in the numerators of Eqs. (1)–(3) above, the first difference for each of the variables was taken between the leg with the higher average power for that variable at 60 rpm minus the other leg and then this order between the two legs was used for all remaining differences. Accordingly, the subscripts ‘high’ and ‘low’ in the equations represent the leg that produced the higher and lower averages, respectively, for the particular power quantity of interest. Note that with this computational scheme, different legs for the same subject could serve as the 60 rpm reference. For example, if a subject produced $\bar{P}_{\text{pos,high}}$ with the right leg at 60 rpm and $\bar{P}_{\text{leg,high}}$ with the left leg at 60 rpm, then the right leg was used as the reference in Eq. (1) and the left leg was used as the reference in Eq. (3). In the event that no significant differences were detected for the sample as a whole, a simple linear regression was performed for each subject as a second separate analysis to identify significant linear trends in the variables ($p < 0.05$) as a function of pedaling rate.

To analyze any asymmetry associated with the dominant leg, the dependent variables defined by Eqs. (1)–(3)

were computed except that the difference was taken between the kicking dominant leg minus the other leg. To investigate whether the kicking dominant leg contributed more average power than the non-dominant leg, paired *t*-tests were performed on each of the three variables. All data for the five pedaling rates and the 11 subjects were included in these tests. To investigate whether this definition of asymmetry changed with pedaling rate, the same procedures of statistical analysis were used as described above for the 60 rpm reference (third of the separate regression analyses) except that regressions for individual subjects were not performed.

3. Results

Of the three dependent variables that were defined to quantify power differences between the two legs when the difference for each of the variables was taken between the leg with the higher power at 60 rpm minus the other leg, only the percent difference in average negative power (%AN) showed a significant linear relationship with pedaling rate ($p = 0.002$). As the pedaling rate increased, the %AN decreased from 29% at 60 rpm to 10% at 120 rpm (Table 1). Neither the percent difference in average positive power (%AP) ($p = 0.626$) nor the percent difference in total average crank power (%AC) ($p = 0.476$) showed a significant linear relationship.

When the subjects were examined for kicking dominance, ten of the 11 subjects were right-leg kicking dominant. All subjects were right handed except one subject who was left handed. The subject who was left handed was also left-leg kicking dominant.

When the data for the kicking dominance were analyzed, the dominant leg contributed significantly less to both the percent difference in average positive power (%AP) ($p = 0.004$) and the percent difference in average negative power (%AN) ($p < 0.001$) than the non-dominant leg. However, the kicking dominant leg contributed significantly greater average crank power (%AC) ($p = 0.04$) than the non-dominant leg (Table 1). Notwithstanding these significant differences, no significant linear relationship with pedaling rate ($p > 0.180$) was evident for any of these quantities.

Although examination of the group mean pedal force and joint moment data revealed that the group was relatively symmetric in their pedaling mechanics, examination of individual subject data revealed substantial differences between legs. For the example subject whose data are shown in Fig. 1, the non-dominant leg exhibited higher peak positive and negative horizontal pedal force components and the non-dominant leg developed more vertical pedal force than the dominant leg throughout most of the crank cycle. Similar trends were observed for the intersegmental joint moment profiles (Fig. 1d–f). The non-dominant leg contributed

Table 1
Group mean values of the pedaling rate, total average power, and asymmetry quantities

RPM	Average power			% Average pos power ^b		
	Kicking	Non	Both	Kicking	Non	%AP
59.5	132.7	130.2	262.9	49.9	50.1	− 0.1
74.9	129.5	128.3	257.8	49.6	50.4	− 0.8
88.8	131.0	129.0	260.0	49.3	50.7	− 1.4
104.7	131.3	126.3	257.7	49.3	50.7	− 1.5
118.3	130.2	126.5	256.6	49.1	50.9	− 1.8
	% Total power ^b			% Average neg power ^b		
RPM	Kicking	Non	%AC	Kicking	Non	%AN
59.5	50.5	49.5	0.9	43.8	56.2	− 12.5
74.9	50.3	49.7	0.5	46.3	53.7	− 7.5
88.8	50.4	49.6	0.8	44.9	55.1	− 10.1
104.7	51.0	49.0	2.0	43.8	56.2	− 12.5
118.3	50.7	49.3	1.4	45.0	55.0	− 10.1
	Average power			% Average pos power ^b		
RPM	Pwr_60	Non	Both	Pwr_60	Non	%AP
59.5	134.6	128.2	262.9	51.1	48.9	2.2
74.9	132.0	125.8	257.8	51.2	48.8	2.3
88.8	132.7	127.3	260.0	51.2	48.8	2.4
104.7	130.9	126.7	257.7	51.0	49.0	2.0
118.3	129.9	126.7	256.6	50.9	49.1	1.8
	% Total power ^b			% Average neg power ^{a,b}		
RPM	Pwr_60	Non	%AC	Pwr_60	Non	%AN
59.5	51.2	48.8	2.4	64.6	35.4	29.1
74.9	51.2	48.8	2.4	60.6	39.4	21.2
88.8	51.1	48.9	2.1	58.1	41.9	16.3
104.7	50.8	49.2	1.6	56.1	43.9	12.2
118.3	50.7	49.3	1.3	55.0	45.0	10.1

^aSignificant linear relationship with pedaling rate.

^bSignificant difference between legs from paired *t*-tests.

substantially more than the dominant leg at the hip, knee, and ankle joints.

The simple linear regression on the percent difference in average crank power (%AC) for individual subjects revealed that four of the 11 subjects had a significant linear trend with pedaling rate (Table 2). Of the four subjects, three exhibited a cross-over effect as pedaling rate increased (i.e. the leg generating greater average power changed) (Fig. 2). Of these three subjects, two (subjects 2 and 4) switched from the kicking dominant to the non-dominant leg while the third (subject 5) had the opposite trend. The fourth subject (subject 6) increased asymmetry with the kicking dominant leg as pedaling rate increased. No significant linear relation with pedaling rate was evident for any of the remaining seven subjects (Table 2, Fig. 3).

4. Discussion

The objectives of this study were to (1) determine whether bilateral asymmetry in cycling changed systematically with pedaling rate, (2) determine whether the dominant leg as identified by kicking contributed more to average power over a crank cycle than the other leg, and (3) determine whether any dominant leg asymmetry changed systematically with pedaling rate. To achieve these objectives, pedal kinematic and kinetic data were collected from a sample of 11 subjects and three measures of asymmetry defined by Eqs. (1)–(3) were computed based on the power supplied by each leg to the crank arm. In addition, intersegmental moments were also computed. Although only the quantities computed from Eqs. (1)–(3) were analyzed statistically, the moment computations were valuable to this study since they both demonstrated the source of the asymmetry and also aided in interpreting differences in crank power quantities. Before discussing the results in light of the stated objectives, one aspect of the experimental procedures merits some discussion.

Because each subject was tested on a single day and the workrate was demanding, the effects of fatigue were considered in the design of the testing protocol. As the subjects become fatigued, power production may switch between legs to maintain the required power output. McCartney et al. (1983) found that the difference in maximal peak torque production between legs was less than 10% at the beginning of a 45 s maximal effort pedaling test in most of their subjects, but that this difference increased to greater than 15% towards the end of the test. To prevent fatigue from influencing the results in the present study, well-trained competitive cyclists were used and the order of the pedaling rates was randomly assigned within each subject.

The hypothesis that the pedaling asymmetry quantities would change systematically with pedaling rate disregarding any measure of dominance was supported, but only for the percent difference in average negative power. Although not presented in the Results, it is interesting to note that the regression results on this same quantity for the individual subjects indicated that only three of the 11 subjects exhibited significant relationships. However, the percent difference in average negative power was consistently lower at 120 than 60 rpm for all of the subjects thus yielding the significant relationship for the subject sample. This result indicates that the asymmetry becomes less pronounced as the pedaling rate increases.

The hypothesis that the dominant leg as identified by kicking would contribute more average power than the other leg was supported. Because the dominant leg contributed more to the total average crank power at all pedaling rates (range 0.5–2.0%) (Table 1), the difference between the two legs was statistically significant despite

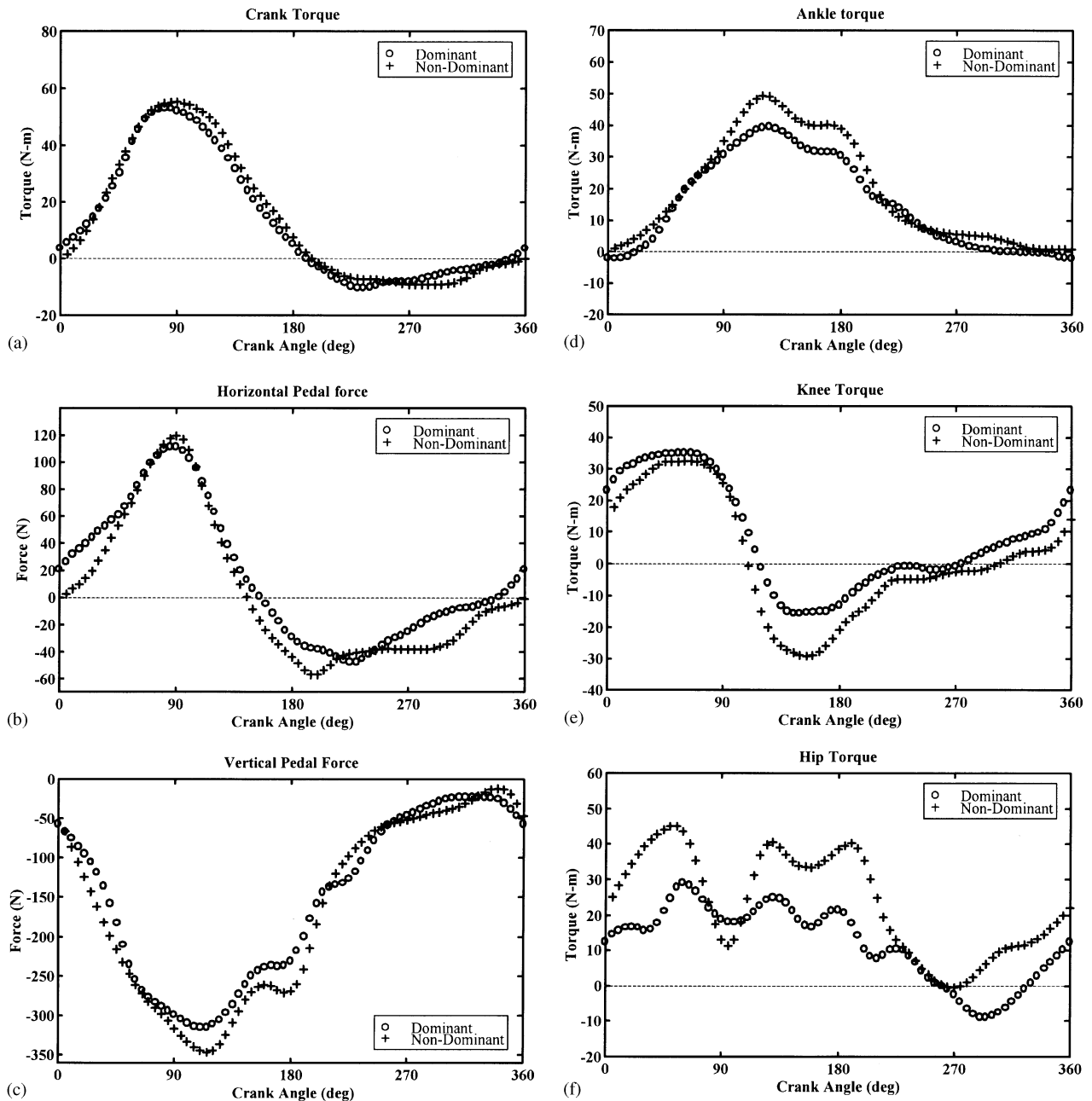


Fig. 1. (a)–(f). Representative subject's pedaling mechanics and intersegmental joint moments. Subject was right leg kicking dominant. The crank angle is 0° at top-dead-center and positive in the clockwise direction. For the pedal force components, the horizontal force was defined as positive towards the front of the bicycle and the vertical component was positive upwards. For the intersegmental moments, positive is extension and negative is flexion.

the relatively small (1.1% average across pedaling rates) difference.

Although the dominant leg contributed more average crank power than the non-dominant leg, an interesting result was that the positive average power of the dominant leg was significantly less than that of the non-dominant leg. This occurred for seven of the 11 subjects tested because the non-dominant leg developed a greater hip extensor moment during the downstroke than the dominant leg. Similar findings were observed in the knee

joint moment where the non-dominant leg had a substantially larger knee flexor moment which has been shown to be important in providing power to the crank (e.g. Fregly and Zajac, 1996).

Offsetting the statistically significant increase in the average positive power in the non-dominant leg was a corresponding statistically significant increase in the average negative power. This increase in average negative power was highly consistent among subjects being exhibited by nine of the 11 tested. Daly and Cavanagh

Table 2
Linear regression analysis for each subject on percent difference in average power per leg.

Subject	p-value	Comment
1	0.096	No systematic change
2	0.007 ^a	Cross-over in asymmetry
3	0.448	No systematic change
4	0.008 ^a	Cross-over in asymmetry
5	0.050 ^a	Cross-over in asymmetry
6	0.003 ^a	Increase in asymmetry
7	0.876	No systematic change
8	0.671	No systematic change
9	0.274	No systematic change
10	0.150	No systematic change
11	0.319	No systematic change

^aSignificant linear relationship with increased pedaling rate ($p \leq 0.05$).

(1976) also noted the appearance of negative crank torque during the recovery phase, particularly for the non-dominant side. The increased negative crank torque on the non-dominant side are likely related to either

a strength or coordination deficit of the hip flexor muscles as evidenced by smaller hip flexor torque during the upstroke region of the crank cycle (Fig. 4d).

Although significant differences were evident in all three quantities between the kicking dominant leg and the non-dominant leg, the hypothesis that any asymmetry associated with the kicking dominant leg would change systematically as pedaling rate varied was not supported. Neither of the hypotheses investigating asymmetry changes with pedaling rate was supported because of the large variability among the subjects. For example, only four of the 11 subjects showed any significant relationship on the percent difference in total average power (Table 2) and variability was evident in the cross-over behavior in these relations among the four subjects. These results suggest that changes in pedaling asymmetry with pedaling rate are very subject specific.

The subject that increased average power asymmetry with the dominant leg (Fig. 2, subject 6) increased asymmetry from 6% at 60 rpm to 16% at 120 rpm. This result is consistent with McCartney et al. (1983) who also had

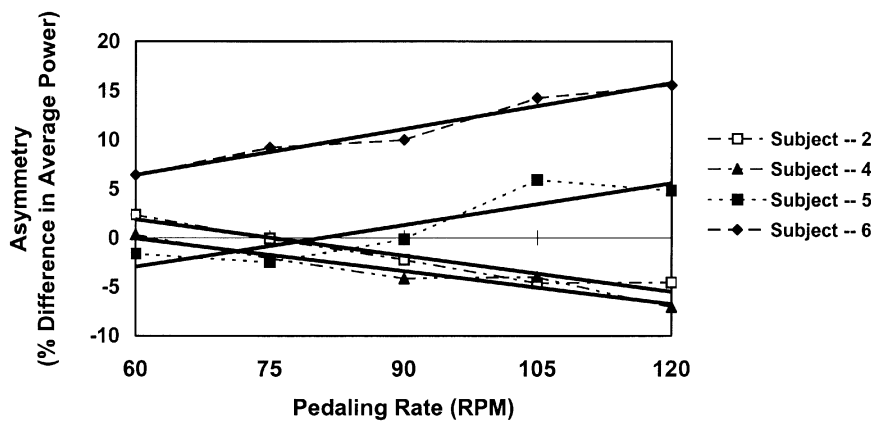


Fig. 2. Linear regression plots of the four subjects who exhibited significant linear trends with increased pedaling rate. The dependent variable is the percent difference in total average crank power of the kicking dominant leg minus the other leg normalized to total average crank power.

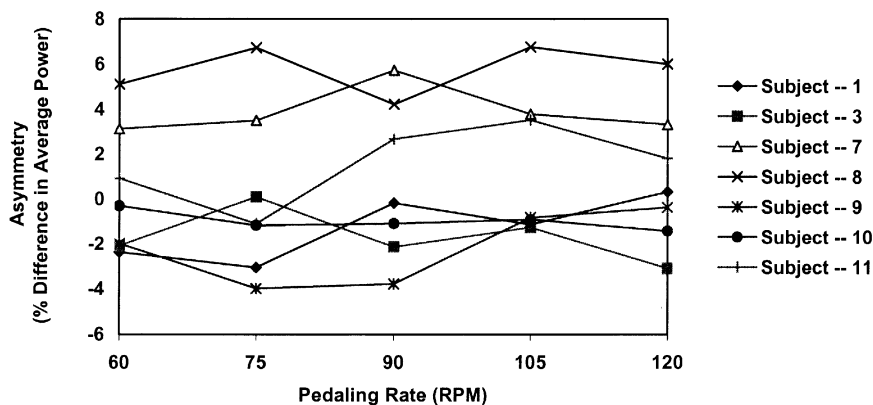


Fig. 3. Data of the seven subjects who did not exhibit significant linear trends with increased pedaling rate. The dependent variable is the percent difference in total average crank power of the kicking dominant leg minus the other leg normalized to total average crank power.

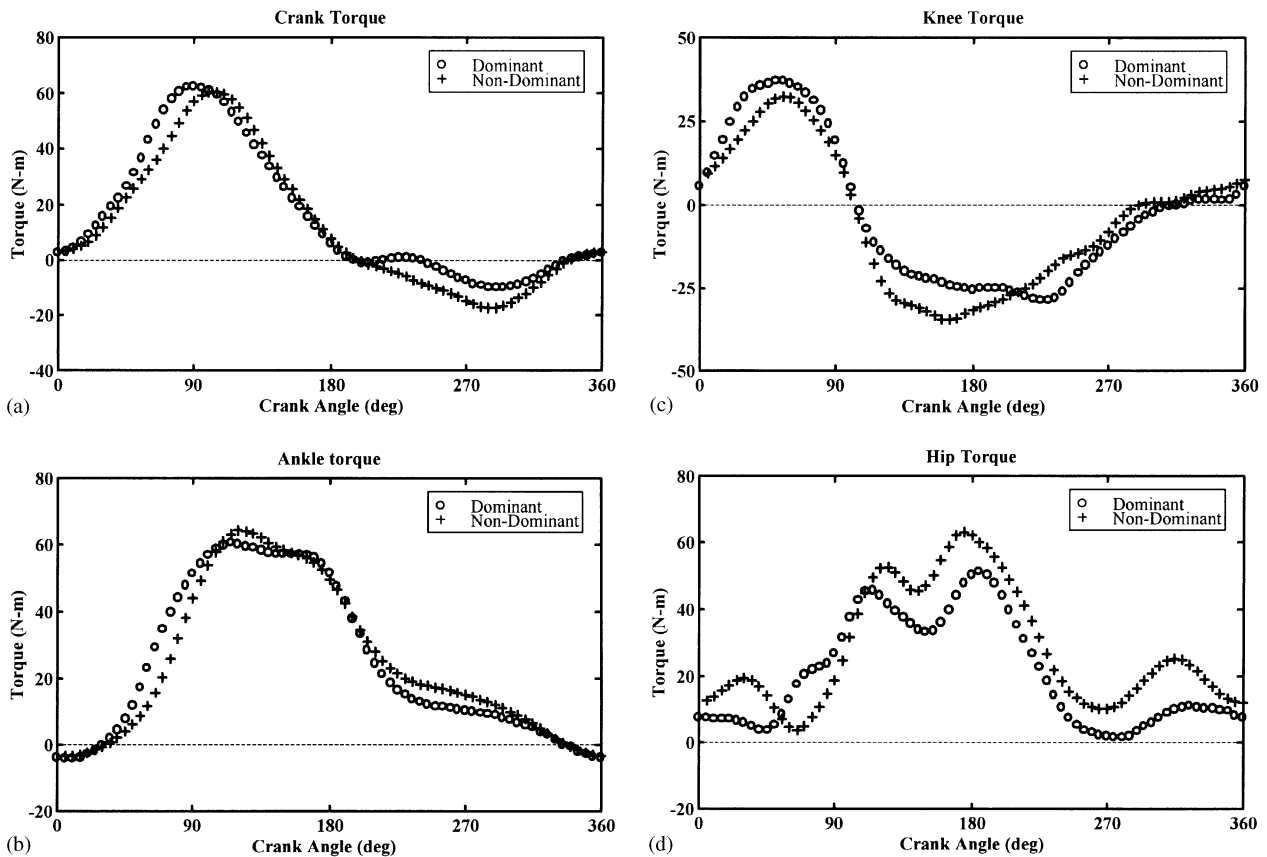


Fig. 4. (a)–(d). Crank torque and joint moment profile comparison between legs for subject 6 at 120 rpm. Subject 6 was right-leg kicking dominant.

a subject who increased peak torque asymmetry from 7% at 60 rpm to 28% at 160 rpm. For the subject in the present study, the joint moments and crank torque profiles at 120 rpm reveal the mechanics associated with the asymmetry (Fig. 4). Although the ankle moment patterns are similar between the two legs, substantial differences exist between the knee and hip patterns. During the power phase (0–90°), the dominant leg contributes substantially to the knee moment with a peak moment 18% higher. At bottom-dead-center (180°), the dominant leg has a higher peak flexor moment which is important to propelling the crank through this region (e.g. Fregly and Zajac, 1996). The most profound difference is observed in the hip moment during the upstroke (180–360°). The non-dominant leg exhibits a substantially higher hip extensor moment that hinders crank propulsion. These differences may be the result of strength differences and/or motor control deficits in the non-dominant side. A training or exercise program focusing on the strength and coordination across the hip joint may reduce the amount of asymmetry and potential for injury while improving performance.

A comparison of the magnitude of asymmetry with previous studies illustrates the variability within subjects depending on the quantity measured. Sargeant and

Davies (1977) observed bilateral differences in applied pedal forces up to 3% while LaFortune et al. (1989) observed differences in mean pedal force work up to 16%. Cavanagh et al. (1974) found 1–42% of asymmetry in the total work output between legs which was a similar quantity to our normalized average power output which ranged from 3–15% across subjects, but was not found to be statistically significant. The higher values found by Cavanagh et al. (1974) could be related to differences in the experimental protocol (i.e. shoe–pedal connection and trained versus untrained subjects).

Overall, the results of this study indicate that although pedaling asymmetry is related to limb dominance, changes in asymmetry with pedaling rate are highly subject specific and unrelated to limb dominance as identified by kicking. Musculoskeletal and motor control differences between limbs may play an important role in determining limb dominance. Future studies incorporating electromyography data may help to identify motor control differences by quantifying differences in muscle coordination (i.e. muscle activation timing and magnitude). This information would be important in not only understanding normal motor control asymmetries, but also in providing insight into pathological motor control deficiencies.

The results are also useful in guiding the development of mathematical models to simulate cycling biomechanics over a range of pedaling rates (e.g. Neptune and Hull, 1998). With all but one of the asymmetry quantities being unaffected significantly by pedaling rate changes, there is no need to incorporate any systematic asymmetry changes to accurately simulate cycling biomechanics at different pedaling rates.

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