World Academy of Science, Engineering and Technology
International Journal of Sport and Health Sciences
Vol:14, No:5, 2020

Significance of Bike-Frame Geometric Factors for Cycling Efficiency and Muscle Activation

Luen Chow Chan

Abstract**—**With the advocacy of green transportation and green traveling, cycling has become increasingly popular nowadays. Physiology and bike design are key factors for the influence of cycling efficiency. Therefore, this study aimed to investigate the significance of bike-frame geometric factors on cycling efficiency and muscle activation for different body sizes of non-professional Asian male cyclists. Participants who represented various body sizes, as measured by leg and back lengths, carried out cycling tests using a tailor-assembled road bike with different ergonomic design configurations including seat-height adjustments (i.e., 96%, 100%, and 104% of trochanteric height) and bike frame sizes (i.e., small and medium frames) for an assessable distance of 1 km. A specific power meter and self-developed adaptable surface electromyography (sEMG) were used to measure average pedaling power and cadence generated and muscle activation, respectively. The results showed that changing the seat height was far more significant than the body and bike frame sizes. The sEMG data evidently provided a better understanding of muscle activation as a function of different seat heights. Therefore, the interpretation of this study is that the major bike ergonomic design factor dominating the cycling efficiency of Asian participants with different body sizes was the seat height.

Keywords**—**Bike frame sizes, cadence rate, pedaling power, seat height.

Open Science Index, Sport and Health Sciences Vol:14, No:5, 2020 publications.waset.org/10011210.pdf

I. Introduction

NOWADAYS, the bicycle is used commonly around the world as a method of transportation, particularly as green transportation becomes more important [1], [2]. Researchers have dedicated a lot of effort to the study of physiology and bike design to improve the cycling experience [3]-[5]. Numerous studies have focused on triathletes' cycling positions to enhance their performances during competitions and guide their training regimens [6], [25]-[28]. These investigations have included geometric factors such as seat tube angle (STA), seat height and seat position which can affect the cyclist's experience. The most common variables used for analysis are oxygen consumption, kinematics and sEMG.

STA was defined by Price and Donne as the induced angle between the seat tube and the crank axis when it is parallel to the ground [7]. Their study measured efficiency as a function of different STAs. The efficiency was increased significantly to an average value of approximately 20% (the mean of 96%, 100% and 104% trochanteric height) as the STA was adjusted to 74º. Their study also measured oxygen consumption as a function of seat height and STA. The results showed that, at a low STA of 68º, the mean oxygen consumption was significantly higher than for STAs of 74º and 80º. These results concurred with those of a study conducted by Heil et al. [8], although it needs to be noted that 80% of their participants were triathletes who were accustomed to cycling at a steep STA. According to previous research, road racing cyclists prefer STAs between 72º to 76º while triathletes adjust the STA to a higher angle, between 70º to 78º [6]. Bisi et al. focused on biomechanical and metabolic factors as a function of STA [9]. Their results showed that the oxygen consumption remained unchanged with STA angles of 73.5º and 78º. Verma et al. examined cyclists' discomfort levels as a function of different seat positions and STAs during cycling [10]. Their results showed that the discomfort score, measured using an electronic visual analogue scale, was dependent on seat position. An increased discomfort score was measured as the seat position was adjusted upward, downward, forward and backward compared to the neutral cycling position of 106% and 107% of crotch height for males and female, respectively [11].

sEMG is a non-invasive electrodiagnostic procedure to evaluate and record the comprehensive effect of electrical activity generated on skin surface [12]-[14]. There have been very few academic studies of STA as a function of muscle activation. Ericson et al. managed to discover the relationship between seat height and gastrocnemius muscle, with the sEMG in the gastrocnemius muscle decreased as the seat height was adjusted to higher positions [15]. Sanderson et al. investigated the relationship between seat height and muscle excitation, finding that muscle contraction and length are the main factors that affect force generation [16]. Three different seat heights of 92%, 102% and 107% of trochanteric height were selected, corresponding respectively to low, neutral and high seat positions. They analyzed the muscle length and contraction velocity of soleus and medial gastrocnemius muscles as a function of the crank angle. A decrease in sEMG was observed at low seat height. As the seat height was adjusted to neutral and high positions the sEMG increased significantly. A further study of sEMG in relation to seat position was conducted by Verma et al. [10]. They found that the mean sEMG of the gastrocnemius muscle decreased significantly in the forward and downward position compared to the neutral position.

The objective of the experiment reported here was to examine cycling efficiency in terms of pedaling power and cadence with small and medium bike frame sizes and different seat heights. Cyclists with various body sizes were selected to participate in this study. Road bicycles were used in this experiment.

L. C. Chan is with The Hong Kong Polytechnic University, Kowloon, Hong Kong S.A.R., China (e-mail: lc.chan@polyu.edu.hk).

II. METHODS

A. Participants

All participants were students and from the Department of Industrial and Systems Engineering, at the Hong Kong Polytechnic University. They were all non-professional athletes and cyclists, with the age (mean ± standard deviation), height, and body mass of (22.4 ± 1.4) years, (172.3 ± 5.4) cm and (65.7 ± 8.0) kg, respectively. The measured leg and back lengths of cyclists are shown in Fig. 1 A. They did not have any advanced cycling experience and had not participated in any special training or preparation before the experiments. However, they were physically healthy and did not have any injuries. Before the experiments commenced, all participants were well-hydrated and allowed 30 seconds to warm up to prevent injuries. The participants were fully aware of the experimental details and signed an informed consent statement that conformed to the guidelines of the university. This study received the ethical approval from the Human Subjects Ethics Sub-Committee (HSESC) of the Hong Kong Polytechnic University in 2016.

Fig. 1 Schematic diagrams of (A) the measured leg and back lengths of cyclist riding the bicycle, and (B) the configurations of small (S) and medium (M) size bike frame employed in this study

B. Location & Environment

The experiments took place outdoors with an environmental temperature and humidity of 33 ˚C and 80%, respectively. The temperature was measured using commercial software called Pioneer provided by Cyclo-Sphere. The humidity was recorded based on the information provided by the Hong Kong Observatory. The purpose of performing the experiments outdoors was to simulate daily outdoor cycling experiences. Although the surface of the floor was not perfectly flat, this should not have influenced the results significantly.

C. Bike Configurations for Testing

A self-developed road bicycle was used in this study. A schematic diagram of its configurations is shown in Fig. 1 B. The purpose of using a road bicycle was because this is the type commonly used on flat roads; therefore the cycling efficiency could reflect the cyclist's performance closely. The frame was made from aluminum [17] and designed by the Net Shape Manufacturing Technology Unit (NSMTU) in the Hong Kong Polytechnic University. The key features defining the size of the frame were handlebar height, top tube length and top tube height. In this study, two different bicycle sizes of 47 cm (small size) and 58 cm (medium size) with a fixed crank length of 170 cm were used. The measurements of the frame sizes were based on the top tube length where there was a separation distance between the seat tube and the head tube, as illustrated in Fig. 1B. This diagram also shows the dimensions of the small and medium frames. A height STA of 74.2º was selected and the remained unchanged for both frames [7].

Three different seat positions were selected for this study, neutral, upward and downward. These corresponded with 100%, 104% and 96% of the participants' trochanteric heights [18]. Screws were loosened to adjust the seat height to the desired position. The height was measured using a measuring tape with an approximate error of ± 0.2 cm [7].

D. Experimental Protocol

The participants were requested to finish three trials with different saddle heights of 96%, 100% and 104% TH, all on the same day. The participant's systolic blood pressure, diastolic blood pressure and pulse were measured and recorded before the experiment commenced. After the trial, the participants rested until their systolic, diastolic blood pressure and pulse value returned to the initial state before starting the second trial. Again, there was 30 seconds warm up time allowed for each participant before the experiment commenced. The participants were allowed to drink water and consume refreshments during this interval. The participants cycled at their best cadence rates for 1 km [19] with their hands placed on top of the handle bar, as shown in Fig. 2.

E. Data & sEMG Acquisition

SGX-CA500 Pedaling sensors provided by Pioneer were used to analyze the cyclists' performances in real time. A pair of sensors was attached, one on either side of the cranks. These sensors were capable of measuring mean pedaling power and cadence in real time. These values were used in this study to compare the variations in frame sizes and seat tube heights.

The pedaling power was measured when the pedaling monitor sensor was used in power meter mode. The power meter measured the pedaling power using a combination of strain gauges and torque applied to the pedals. The rotational frequency was calculated from the cadence rate; therefore the power generated in angular motion was derived as:

$$P = \frac{dW}{dt} \tag{1}$$

where P is the power, W is the work done and t is the time. W can be expressed as:

$$W = Fs \tag{2}$$

where F is the force and s is the displacement. For an angular motion, the displacement is:

$$s = \theta r \tag{3}$$

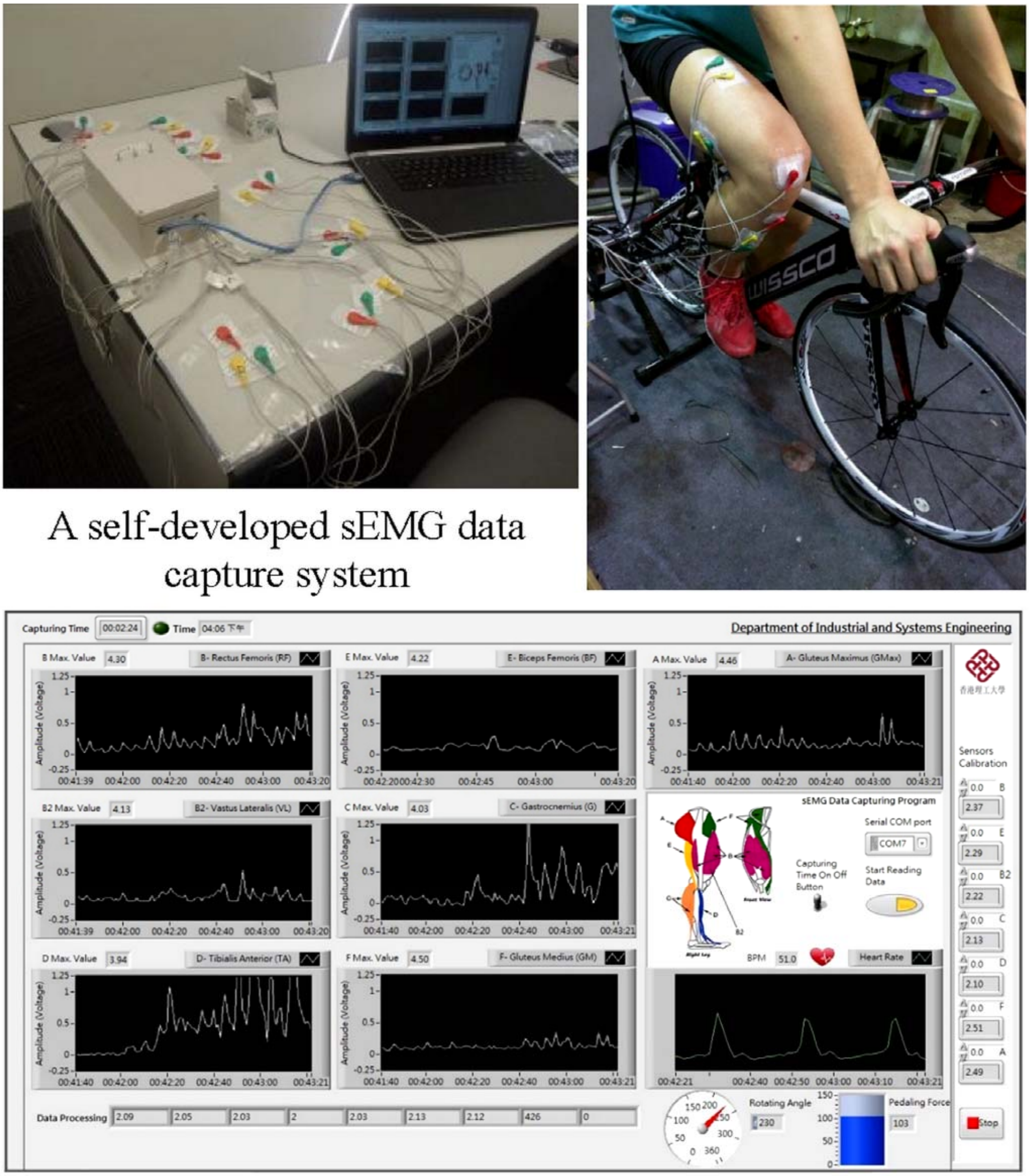

Fig. 2 Cyclist's posture during the experiments with the self-developed sEMG sensors attached to the cyclist's muscles

where θ is the angle in radians and r is the radius. Therefore, (2) is now expressed as:

$$W = F\theta\, r \tag{4}$$

Since the expression of torque (T) is defined as:

$$T = r \times F \tag{5}$$

Therefore, (4) can be re-written as:

$$W = T\theta \tag{6}$$

Combining (1) and (5),

$$P = T\theta/dt \quad (7)$$

Since the angular velocity (ω) is defined as:

$$\omega = \frac{\theta}{dt} = 2\pi f \quad (8)$$

where f is the frequency. Therefore, (7) can be written as:

$$P = T \cdot 2\pi f \quad (9)$$

The cadence was defined as the number of rotations of the crank in a period of one minute and the unit was rotations per minute (rpm). Before the experiment, the sensors were calibrated by following the manufacturers' guidelines. The data were uploaded through Pioneer Cycle Cloud Connect to Cyclo-Sphere. Data from the entire 5 minutes were averaged out for analysis.

A three-lead differential muscle/electromyography sensor provided by Advancer Technologies was used to measure muscle activation. In this study, three different sets of right leg muscles were measured: vastus lateralis (VL), gastrocnemius (G) and tibialis anterior (TA) [16], [20], [21]. Before the sensors were attached to the skin of the targeted muscle groups, they were cleaned thoroughly to reduce impedance. sEMG signals were recorded using 300 Hz sample rate. The muscle activation data were acquired using a LabVIEW program for further analysis. Before the electrodes were attached to targeted muscles, the skin which made intimate contact with the electrodes was shaved, 300 grade sand paper was applied to remove any dead skin, and the skin was eventually cleaned using isopropyl alcohol.

III. Results

A. Average Pedaling Power and Cadence Cycling from Different Sizes of Bike Frames

In the experiments, three sets of body dimensions, arm, leg and back lengths, were studied and characterized. These values were compared after the cycling performance using two different sizes of bike frames (small and medium) and seat heights. The data from Fig. 3 were obtained from the cyclo-sphere, which recorded the average pedaling power and cadence of two groups of cyclists with different body dimensions.

Figs. 3 A-D show the average pedaling power generated from two groups of cyclists based on their leg and back lengths. The cyclists were divided into two groups, long and short leg lengths between 990 mm – 1040 mm and 849 mm – 903 mm in Figs. 3 A and, and long back and short back lengths between 634 mm – 731 mm and 589 mm – 625 mm in Figs. 3 C and D. In general, cycling at a low seat height generates the highest amount of pedaling power. A high seat height was unfavorable for generating pedaling power compared to neutral and low heights. It can be seen that the mean values of the pedaling power decreased progressively as the seat height was adjusted to higher positions. The maximum value of 137.7 ± 40.1 pedaling power was recorded by the short-back group at the low seat height with the small bike frame. A similar value of 130.7 ± 2.2 W was also measured at the low seat height in the medium bike frame experiments. The trendline plotted in Figs. 3 C and D is similar to Figs. 3 A and B, where the highest values of the average pedaling power were always obtained at the low seat position.

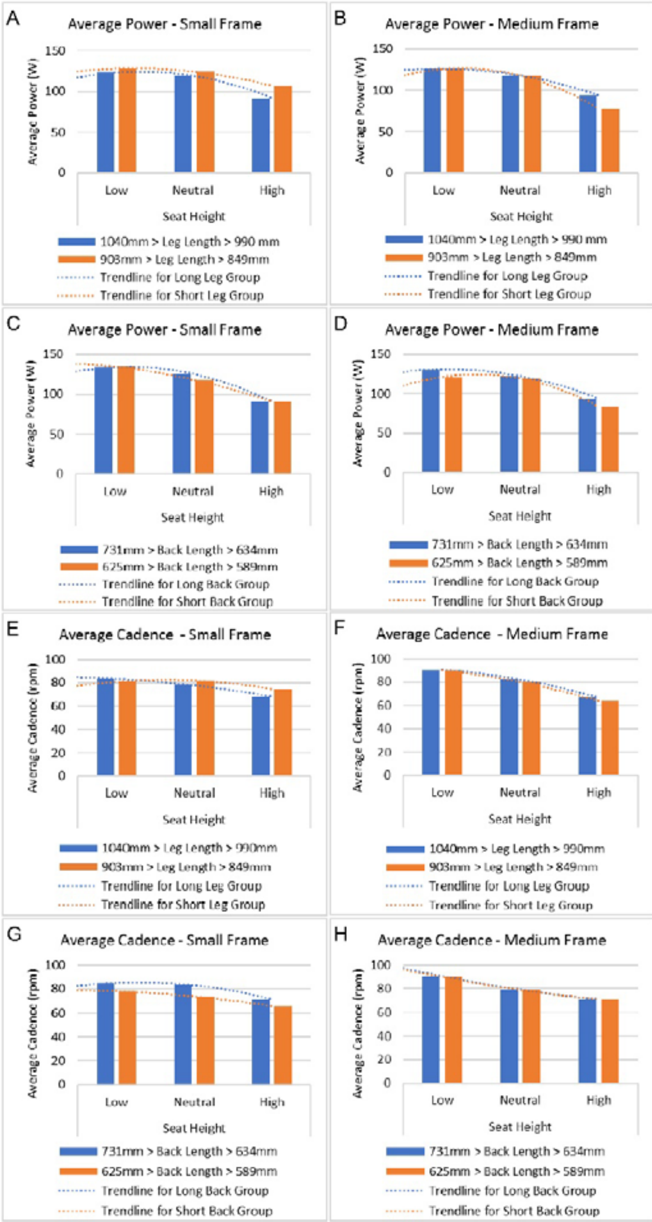

Fig. 3 A-D The average pedaling powers and E-H the average cadence of cycling using the small and medium frames were recorded and plotted as a function of low, neutral and high seat heights

The cadence refers to the number of rotations of the crank and was measured in rounds per minutes (rpm). Figs. 3 E-H showed the mean value of cadence, which was the rate averaged over the 1 km cycling distance. Figs. 3 E and G show the results for the small bike frame. Figs. 3 F and H show that the best cadence of 90.6 ± 10.0 rpm was obtained when the medium bike frame was used at the low position. The lowest cadence value was obtained from the short leg length group at the high seat position of 63.8 ± 13.4 rpm. In this study, the trendline of the cadence showed a similar pattern to the pedaling power, the cyclists were unable to generate high cadence and pedaling power at the high seat position.

The cyclists were categorized into four different groups and their cycling experiences were observed with respect to the combinations of leg and back lengths, as shown in Figs. 4 A-H. After combining the leg and back lengths, the pedaling power and cadence showed similar trends to those shown in Fig. 3. The highest power and cadence generated from the group of cyclists were always at the low seat height position, except for the short leg with long back cyclists cycling at the neutral position. High seats were unfavorable for producing advanced cycling experiences. The data acquired from this study indicated that the dimensions of the leg and back lengths did not influence the pedaling power and cadence significantly. The main, critical factor in producing high pedaling power and cadence was the seat height.

B. Normalized Maximum sEMG

Figs. 5 A-C demonstrate the angle of measurement for the normalized maximum sEMG. The values were averaged for all participants regardless of the body sizes. Table I also illustrates the numerical values referred to in Figs. 5 A-C. The highest sEMG of gastrocnemius (G), tibialis anterior (TA), and vastus lateralis (VL) were measured in a range between 27.7°-288°, 48.9°-285° and 8.5°-97.3°, respectively. The data showed that the size of the bike frames seemed to have no influence on the pattern of the maximum sEMG angle. However, it was rather easy to observe the change in sEMG as the seat height varied from the low to high positions. The lowest maximum sEMG angles were always measured at the high seat position. As the seat height was adjusted to lower positions, the value of the angle increased. This demonstrated that the seat height has primary influence. This phenomenon could be observed in all three sets of muscles, with no exceptions.

IV. Discussion

This study was an attempt to understand the effects of bicycle ergonomic design factors on cycling performance and muscle activation. Previous studies have focused on either triathletes or professional cyclists [6], [8], [26], while the participants selected for this study were non-professional Asian male athletes. sEMG activity was measured from three different sets of right leg muscles, namely gastrocnemius (G), tibialis anterior (TA), and vastus lateralis (VL). The purpose of the sEMG acquisition was to determine the muscle activity as a function of seat height. The cyclists were requested to cycle for an assessable distance of 1 km using two different sizes of bike frame. The average pedaling power and cadence were measured.

The results were rather surprising compared to the previous research studies. The maximum average power was always measured at the low seat height (96% of trochanteric height) position. After the seat position adjusted to the neutral position (100% of trochanteric height), most of the data showed that the power decreased by less than 10% [20]. A rapid deduction in average power was observed once the seat height was increased to 104% of the trochanteric height. This result does coincide with those of [22] and [23], which demonstrated optimum seat heights in the range between 96%-100% of the trochanteric height. A theoretical study [24] showed that the optimum seat height was between 96% and 98% of the trochanteric height. Price and Donne [7] demonstrated the effect of variation in STA at different seat heights. Although their study was focused on efficiency, oxygen consumption and heart rate, their results using 74° seat showed a pattern similar to the 96%, 100% and 104% of trochanteric height. As expected, Figs. 3 and 4 showed the cyclists' average cadence and the pattern was identical to the average pedaling power.

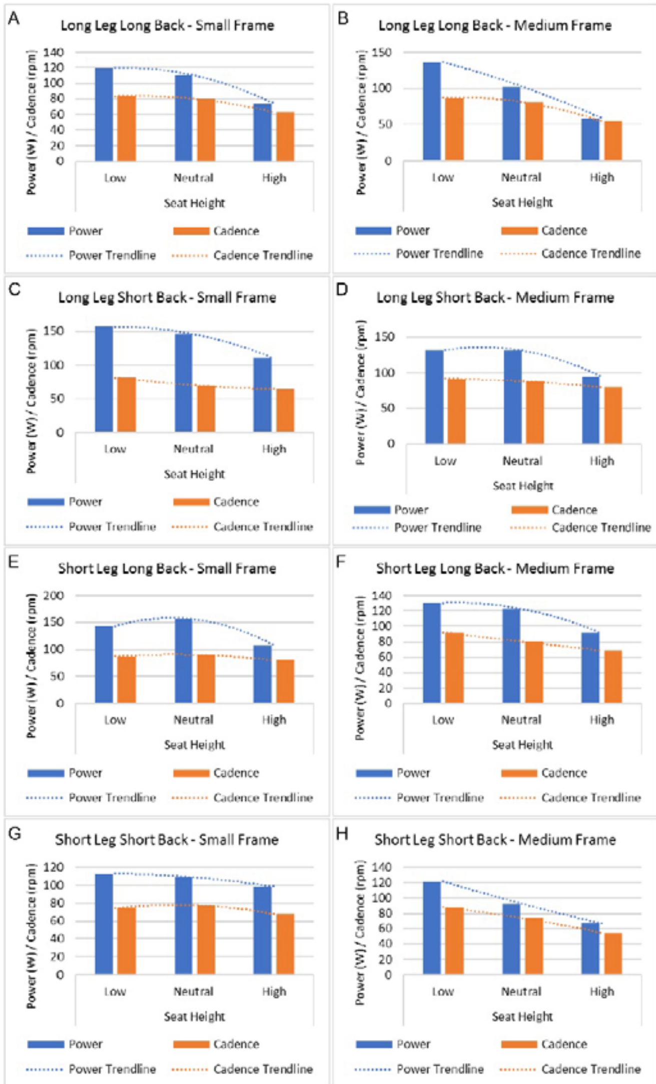

Fig. 4 The combined cyclists with different body sizes as measured by their leg and back lengths. These data also demonstrated the cyclists' performances using different sized bike frames

Sanderson and Amoroso [16] identified that the saddle height management correlated with changes in knee and ankle joint kinematics, with effects from muscle length and force production. Tamborindeguy et al. [18] showed that the change in knee joint kinematics could only be observed using a low seat height but not neutral or high. Their study did not attempt to draw out or optimize the average pedaling and cadence. However, after the trendline was fitted to the data, the optimum seat height was most likely located between 96%-98%.

The purpose of acquiring the sEMG data was to understand how the muscle activation varied as a function of seat height. These results suggest that a shift in the peak angle can be obtained by changing the seat heights. Verma et al. [10] measured the sEMG location in terms of the crank angle for vastus lateralis (VL), gastrocnemius (G) and tibialis anterior (TA). This showed that the maximum crank angles for vastus lateralis (VL), gastrocnemius (G) and tibialis anterior (TA) were located at about 50°, 130° and 300°, respectively.

TABLE I
DATA ACQUISITION OF AVERAGE MAXIMUM SEMG MEASURED AS A FUNCTION OF ANGLES DEDUCED FROM FIG. 5

Frame size	Seat Height	Muscle Group *G*		*TA*		*VL*	
		Average of Maximum sEMG Angle (Degree)					
S size	High	72.9	213.3	66.2	208.5	12.6	54.0
	Neutral	58.2	247.5	67.2	250.0	15.6	64.3
	Low	27.7	288.0	48.9	285.0	24.8	86.8
M size	High	82.5	208.0	63.8	165.0	8.5	66.3
	Neutral	88.4	232.5	60.3	182.8	18.3	79.0
	Low	98.1	261.0	64.0	199.8	21.0	97.3

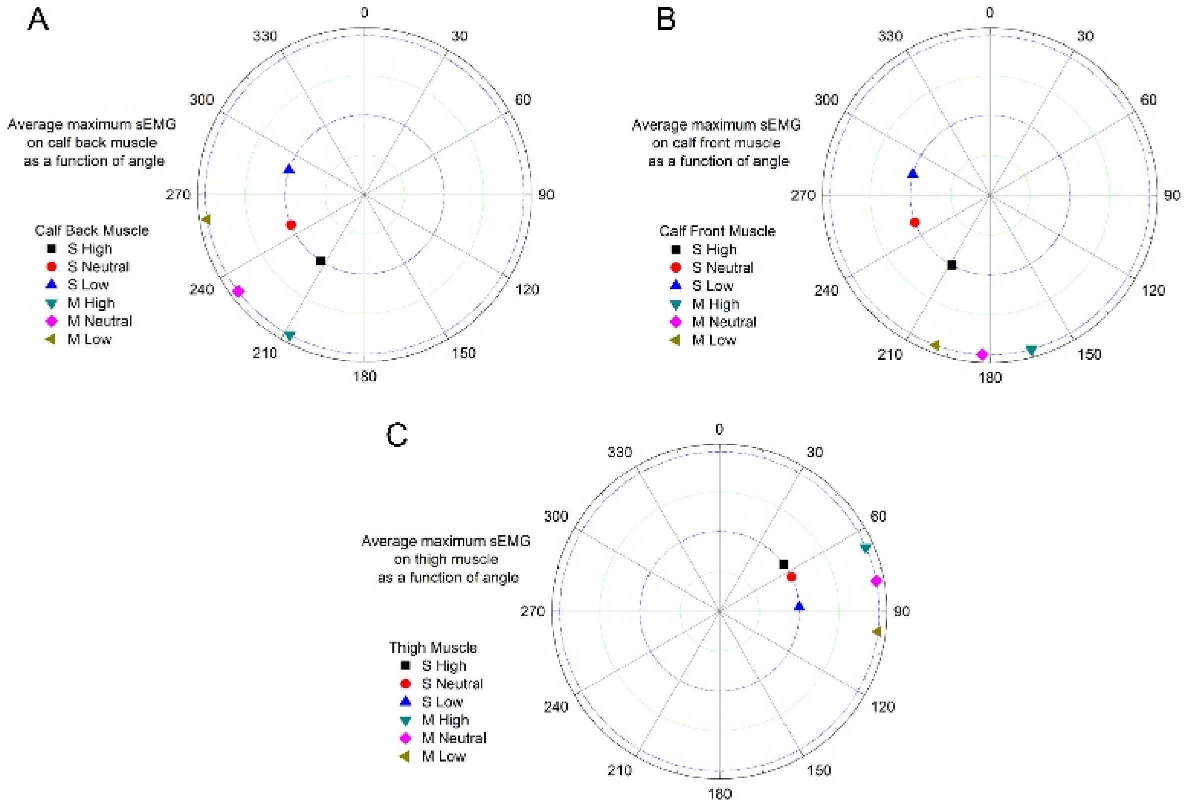

Fig. 5 The average angles where the maximum sEMG values of (A) gastrocnemius (G), (B) tibialis anterior (TA), and (C) vastus lateralis (VL) were acquired

V. PRACTICAL APPLICATIONS

The findings of this study could facilitate determining the more appropriate ergonomic design configurations of such seat heights and bike-frame sizes for cyclists based on their body sizes. The variations of muscle activation and cycling performance such as average pedaling power, and average cadence rate indicated that the cycling posture was significantly influenced by the change of bike geometry and the correct posture could reduce the muscle strain during cycling exercise.

Among different ergonomic design factors, the seat height had the most pronounced impact on the cycling performance of non-professional cycling enthusiasts. When the seat heights were adjusted to the 96% of trochanteric heights of the participants, the overall cycling performances were improved subject to the conditions of casual cycling on a flat road for 1 km distance.

VI. CONCLUSIONS

In conclusion, based on the experimental results, there were no significant changes or evidence that the cyclists' performances were affected by the sizes of the bike frames. The average pedaling power and cadence matched with those in previous studies and demonstrated a similar pattern for the various seat heights. Furthermore, the participants' different leg and back lengths did not influence the average pedaling power and cadence. Changing the seat height was far more significant than the body and bike frame sizes. The sEMG data evidently provided a better understanding of muscle activation as a function of different seat heights. Therefore, this study interpreted that the majority of bike ergonomic design factors dominating the cycling efficiency of Asian participants with different body sizes was the seat height. However, the findings could only apply to non-professionals cycling a distance of 1 km.

Acknowledgment

The work described in this paper was partially supported by a grant from the Research Committee of The Hong Kong Polytechnic University under project code G-UA4K and Innovation and Technology Fund of Hong Kong, ITS-337-14FX (ZM1T) and ITS-015-17FX (ZM2B).

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