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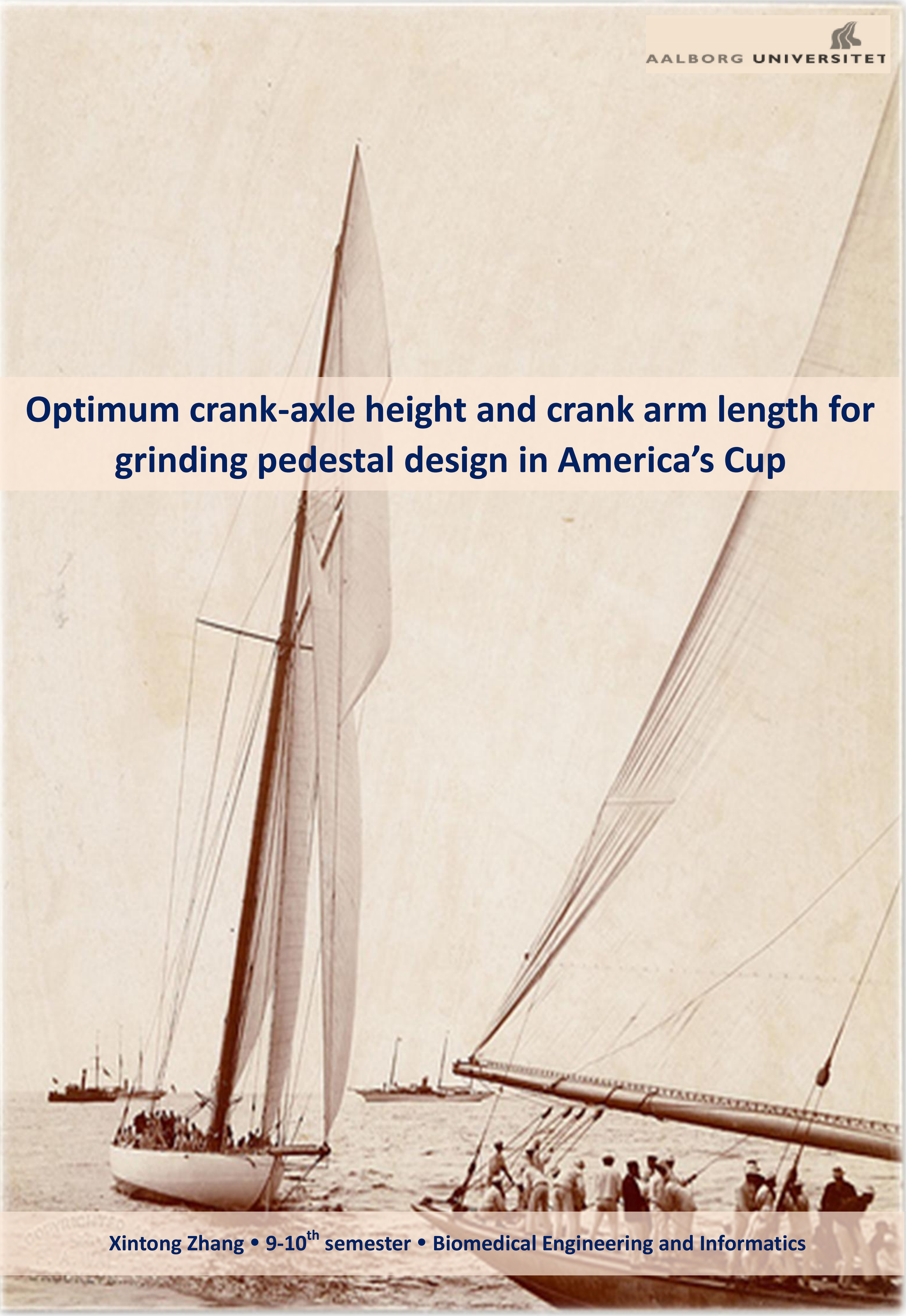

Optimum crank-axle height and crank arm length for grinding pedestal design in America's Cup

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Abstract:

America's Cup is the oldest competing trophy in sport between defenders and challengers. Because of the history and prestige of American's Cup, the world's top sailors, yacht designers and wealthy sponsors are attracted to this popular and perpetual international competition.

To make a great achievement, different roles of the crew do their best to complete special tasks and in addition the equipments have to fit the crew. For instance, the grinders as the main role in the crew, the winches that the grinders work with are required to design to match the grinders' own anthropometric characteristics to allow fast sail handling.

Owing to the correlations between crank-axle height and stature, crank arm length and arm span, this project aims to investigate the optimum combination of crank-axle height and crank arm length according to the percentage of stature and arm span. Subjects perform forward standing grinding with maximum effort for a certain time against a particular resistance. Experiment equipments are designed with SolidWorks, experiment data is recorded via Kick and data analysis is finished by Matlab codes.

From the result of experiment, overall, it could be concluded that the generally optimum combination is 10-10.5 % of arm span and 60-62 % of stature. However, it only works on forward grinding. In America's Cup, two grinders perform both forward and backward grinding together at one winch, the optimum combination that can be applied in backward grinding should be tested in the next step.

Contents

Chapter 1

Introduction

America's Cup is the oldest competing trophy in sport between defenders (the winners of previous America's Cup) and challengers. The trophy was initially awarded in 1851 by the Royal Yacht Squadron which was the most prestigious yacht club in United Kingdom for a race around the Isle of Wight (a country and the largest island of England). The race was won by the schooner American, which resulted in the trophy was renamed the American's Cup after the donation of the yacht to New York Yacht Club under the Deed of Gift (primary instrument with governance of the rules to make a valid challenge for American's Cup and conduct of the races). Because of the history and prestige of American's Cup, it attracts world's top sailors, yacht designers and wealthy sponsors. Subsequently, the race developed into a popular and perpetual international competition.

On the International America's Cup Class version 5 yacht, it typically contains 17 athletes such as bowmen, grinders, trimmers and afterguards to accomplish different tasks including sails hoist and drop, winch turn, shape of sails adjustment, yacht navigation, strategy establishment, etc [1].

The winches attached on the sail lines are driven by grinding which is responsible for the activity of sailing. During the sailing, a large quantity of resistance is put on the grinding system, which can be overcome by producing a large amount of force in a short time (one single tack or gybe) [2].

For instance, in the 32nd America's Cup (April to July 2007 in Valencia, Spain), the average race duration over 135 races was 82 ± 9 min containing 20 ± 10 tacks (upwind turns, 22 ± 3 min each) and 8 ± 3 gybes (downwind turns, 19 ± 3 min each). Each grinding bout respectively lasted 5.5 ± 0.5 s and 11.2 ± 1.4 s for tacking and gybing. There were 143 exercise grinding bouts in total included in one race with an exercise to rest ratio of 1:6 which might increase to 1:3 when applying a higher number of tacks and gybes [1].

Grinding provides power at tacking and gybing in the race and the performance is evaluated by the amount of power produced by grinders [2]. Power is defined as the product of applied force, perpendicular distance of the force from the axis of rotation and angular velocity. In grinding movement, perpendicular distance is considered as the length of crank arm. Applied force mainly lies on anthropometric characteristics such like body mass, height and muscularity. Therefore, both mechanical and human components influence grinding performance. To achieve a great performance, the crew and equipments have to fit each other. For instance, the winches which the grinders work with needs to be designed to match the grinders to allow fast sail handling.

The standard of crank-axel height and crank arm length are 87 cm and 25 cm. As it recorded in the 32nd America's Cup, among 5 teams including 42 grinders totally, the stature of grinders was 1.88 ± 0.05 m, the body mass was 103 ± 7 kg and the age was 32 ± 6 years [1]. The standard crank-axel length used in the race was 46.28 % of stature. Since the average arm span (one finger tip to the other when arms raised parallel the ground at shoulder height at 180 degree angle) correlates approximately equal to the height, the standard crank arm length was estimated 13.30 % of arm span. However, the previous studies point out that it increased the risk of low back injury while grinding at a height below 50 % of stature [3-5]. The feasibility of standard setup of the crank-axel height should be reconsidered. Additionally, these figures are obtained under peak power as the assessment. Nevertheless, the performance of grinding is based on the time when maximum power produces and how long power is maintained after the occurrence of peak power [1], the assessment of grinding performance is better to apply external work, the integration of power for a certain time, which takes both occurrence of peak power and power maintenance into account other than peak power that only concerns about occurrence of peak power.

In this study, both crank-axel height and crank arm length are varied in wide ranges in order to investigate more proper optimum values grounded on external work as assessment.

Chapter 2

Problem analysis

In order to make the research direction clear and discover what knowledge is helpful in the research, the background of grinding, factors of both grinding machine and characteristics of grinders are included, which are the foundation to be gripped.

Grinding supplies the power at tacking and gybing in the race [2]. In terms of grinders themselves, they have high body mass and large body size with low body fat compared to the rest of crew [3] [6] to produce great power and keep high power output for a relatively long time [1]. As for the mechanical equipment (Figure 2.1) which the grinders work with, the pedestal is fixed on the yacht; a pair of crank arms is orientated at 180 degrees mutually, each on one side of pedestal. Handles are situated at the end of crank arms [2].

Figure 2.1: The structure of grinding equipment [2].

2.1 Grinding directions

Grinding direction influences cranking performance [7-9]. Two directions of grinding, both forward grinding (pushing away from body at the top of rotation) and backward grinding (pulling towards body at the top of rotation) are performed by two grinders together at one pedestal during the race [10].

In forward grinding, the sailor typically stood upright, the feet placed behind the body and the body tended to lean over the pedestal (Figure 2.2). This posture generated an upright alignment of the trunk to grinding handles, which was advantageous to apply force during the movement.

The balanced trunk position counteracted instability of base support [11].

In backward grinding, the feet were close to the pedestal, which reduced the benefits of trunk alignment and made it an unstable base of support because of a slide towards anterior direction [11]. Moving the position of center of mass (COM) away from the axis of rotations resulted in an increased shoulder angle which was beneficial for grinders to create force. Moreover, tall grinders with long arms produced long effective lever arms compared to short grinders [12]. With respect to joint kinematics, while considering handle position 0° equaled handle vertically above the hub; position 90° was handle horizontal to the hub travelling from 0°; 180° stood for handle vertically below the hub, 270° meant handle horizontal to the hub moving towards 0°, shoulder angle was measured with trunk as 0° and trunk angle was measured with vertical direction as 0°, sailors tended to have a more ankle flexion and less hip flexion compared to forward grinding (Table 2.1). Shoulder and elbow angles varied slightly at 0° and 180° but remarkably at 90° and 270° [11].

Figure 2.2: Body position during forward grinding and backward grinding [11].

Position	Direction	Ankle	Knee	Hip	Shoulder	Elbow	Trunk
0°	Fwd	103 ±11*	136 ±12	133 ±5*	15 ±15*	93 ±19	39 ±4*
	Back	136 ±8*	134 ±9	101 ±6*	39 ±5*	100 ±14	26 ±5*
90°	Fwd	98 ±9*	134 ±15	128 ±8*	72 ±10*	166 ±7*	46 ±6*
	Back	130 ±10*	131 ±4	106 ±5*	-1 ±9*	92 ±7*	20 ±5*
180°	Fwd	102 ±9*	139 ±12*	122 ±6*	51 ±9	154 ±8	50 ±4*
	Back	124 ±9*	122 ±4*	94 ±11*	47 ±9	162 ±7	33 ±7*
270°	Fwd	114 ±13	150 ±14*	133 ±7*	2 ±7*	105 ±9*	44 ±3*
	Back	127 ±8	123 ±5*	97 ±8*	73 ±10*	162 ±15*	30 ±6*

*Significant difference between forward and backward grinding ($p<0.05$)

Table 2.1: Average joint angles for forward and backward grinding during the revolution [11].

2.2 Muscle activation

Grinding performance relies on muscle activation as well. Electromyography (EMG) is a valid method to measure muscle activation. In orders to examine which muscles play the most important role in forward and backward grinding performance, a previous study [11] designed an experiment for ten grinders to measure EMG of the following muscles: posterior deltoid, latissimus dorsi, triceps brachii, anterior deltoid, pectoralis major and biceps brachii (Figure 2.3). Every subject performed two maximal effort grinding in each of forward and backward directions against moderate-heavy (48-68 N·m) resistance which was scaled according to individual capability (when grinding speed was kept between 90 and 120 rpm for 8 s). The mean EMG activity pattern during both grinding directions for 10 subjects is shown in Figure 2.4, where EMG signal was normalized to a scale of its own activation with 0 % as the lowest signal and 100 % as the highest signal through a period of five revolutions.

In forward grinding, anterior deltoid, pectoralis major and triceps brachii played a dominant role through the top and downward sections (310-150°) and the rest of muscles highly acted through the bottom and upward sessions in the rotation. The minimum point happened at 294° during the upward section, the activity was mainly stimulated by biceps brachii.

In contrast, during backward grinding, the activation occurred to all the testing muscles except for anterior deltoid in the upper half rotation (240-80°), However, anterior deltoid and biceps brachii remarkably worked in the lower half rotation. At the minimum torque which was at 227°, only biceps brachii showed a notable activation, where pectoralis major and latissimus dorsi started to activate.

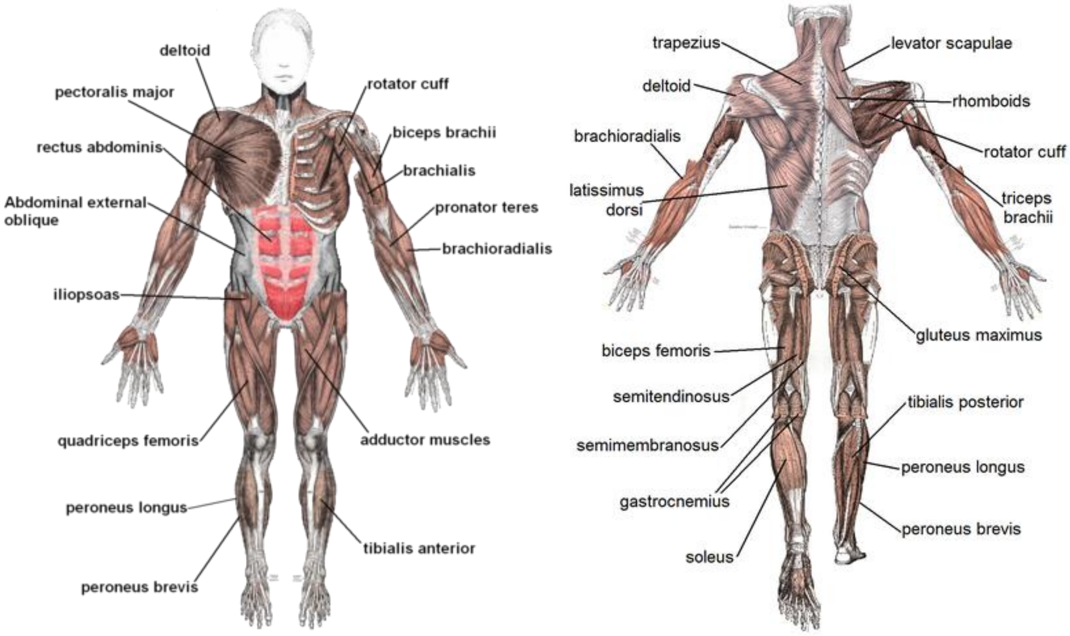

Figure 2.3: Graph of muscles.

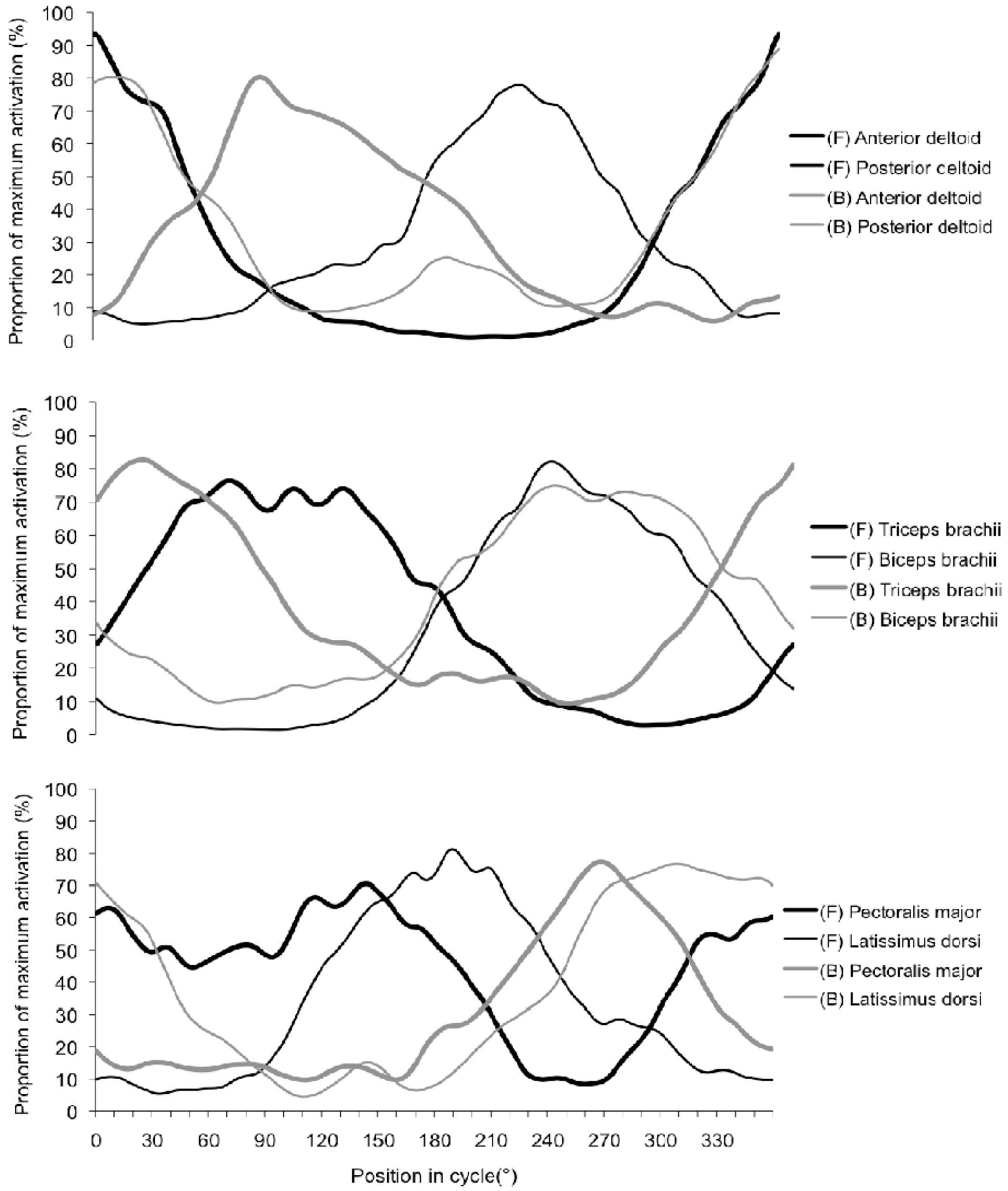

Figure 2.4: Mean EMG during forward (F) and backward (B) grinding. Crank angle travels vertically above the hub is defined as 0°. Crank angle is positive in revolution direction [11].

2.3 Torque application

Torque production is related to the grinding performance. In another word, it presents at which position of the rotation the greatest or weakest force can be generated by the handles. The following content focuses on the study about the effects of grinding direction on torque application [11]. Subjects individually finished two maximum effort grinding in both directions against a moderate-heavy load scaled according to capability. It investigated the data of torque application and angular position collected from grinding handles. Figure 2.5 demonstrates mean torque angle curves for forward and backward grinding. The arrow marks grinding handle rotation direction. Each circle symbolizes 10 N increase of torque and the torque increases when the trace goes away from the center. The position of 0° means handle travels to the point vertically above the hub, and in this graph, it corresponds to vertically upward direction from the center. It could be observed that the greatest torque application were produced via 60-200° with the mean peak torque of 77 N·m at 95° for forward grinding and 300-40° with the mean peak torque of 69 N·m at 35° for backward grinding.

In forward grinding, the greatest amount of work happened when the handles were on the downward part of rotation, which was implemented by shoulder flexion and elbow extension (push movement). To the opposite, the greatest amount of work was generated on the top of rotation by shoulder extension and elbow flexion (pull movement) during backward grinding.

Additional analysis on the relationship between torque application and performance showed the variation in torque through the rotation was negatively connected to forward grinding performance but positively associated with backward grinding performance. It suggested that it was appropriate to focus on maintaining torque through the grinding cycle to enhance forward grinding performance but shift the concentration to pull movement to improve backward grinding. The previous research [10] [13] pointed out that although the maximum force was necessary in both different grinding directions, the difference was that great muscular force related to forward grinding performance the most but high velocity and power were important in backward grinding performance. It was beneficial to improve forward grinding through strength-focused training and backward grinding via speed-focused training.

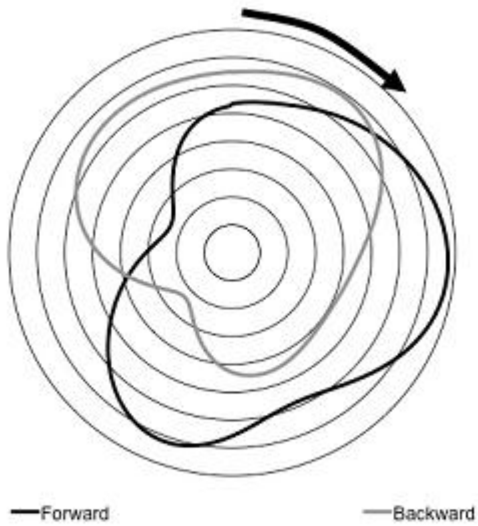

Figure 2.5: Mean torque angle curve for forward and backward grinding [11].

2.4 Anthropometric measurements

This section is based on a master thesis [2]. Some anthropometric measurements recorded possibly influenced the grinding performance. For instance, brachial index defined as a ratio of forearm length to upper arm length, which affected leverage characteristics of upper body [14]. During backward grinding, a high brachial index which meant a relatively short upper arm was beneficial because the hands were able to travel in a linear path that reduced useless lateral force from a curvilinear path of force application.

Another factor, body mass also influenced grinding performance, especially on heavy load grinding. The additional weight could be used to apply more force on the handles via leaning toward handles to assist downward rotation during forward grinding or leaning away from handles to aid upward rotation during backward grinding. In addition, there was no significant disadvantage for increased body mass in performance because the required force was applied via handles other than supporting the body weight. However, in America's Cup, the weight of grinders was restricted to some extent in order to obtain balance for the entire sailing crew.

Total leg length and arm length affected the grinding performance as well. Increasing the distance between COM and the force application point increased torque and improved performance, which indicated long limbs were advantageous for grinding. Lower leg length and trunk length influenced the vertical position between shoulder and the apex of grinding handle [15] [16], particularly short lower legs and trunk length made it easy to keep desired alignment between these two points [17].

2.5 Upper and lower bodies

The most important role of the crew in the race could be considered as grinders who provide the power to turn the winches. Grinding is an activity mainly relying on upper body [18]. The occurrence of peak power and power maintenance upper body generates are main factors influencing grinding performance, which can be accomplished and improved by reducing body fat and increasing muscle mass to keep a high speed of manoeuvres and get rid of fatigue [1] [3].

About the gesture of grinding, one paper points out that the trunk and lower limb should keep in perpendicular position and the hip is not supposed to rotate [19]. Additionally, the midline of trunk should keep stationary to reduce energy waste and maintain balance [11].

The advantageous grinding technique regarding to the role of legs are demonstrated below. Based on the grinding research [18] involving lower body motion, the lower body could play an important role in improving grinding performance. The experiment was completed by eight grinders with free or splinted legs by whether locking the knee joint (Figure 2.6). Two adjacent force plates were used in the vertical ground reaction force (VRGF) test. There was no notable difference in total VRGF calculated as the average over 5 s period for both force plates (Table 2.2), which confirmed that the grinder's weight distribution between feet and ergometer was not influenced by splinting knee joint. However, normal grinding produced greater unilateral amplitude of VRGF calculated from the average of each plate (Figure 2.7), which indicated a shift in body mass between legs during grinding.

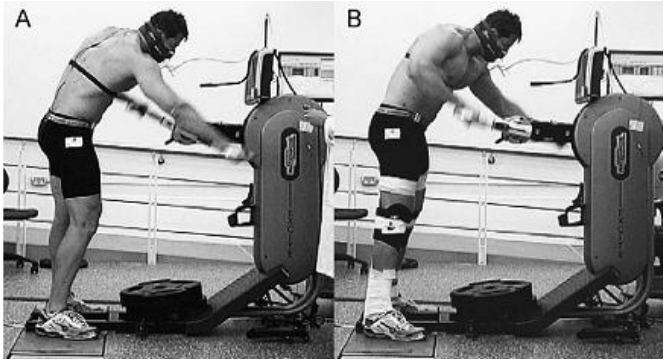

Figure 2.6: Normal grinding (A) and splinted grinding (B) [18].

	VGRFtotal (N)	VGRFamplitude (N)
normal	957 ± 46	776 ± 186*
splinted	967 ± 47	565 ± 180

*Significantly greater than Splinted ($p = 0.01$) Mean ± SD, $n = 8$

Table 2.2: Total VRGF and unilateral amplitude of VRGF between normal and splinted grinding [18].

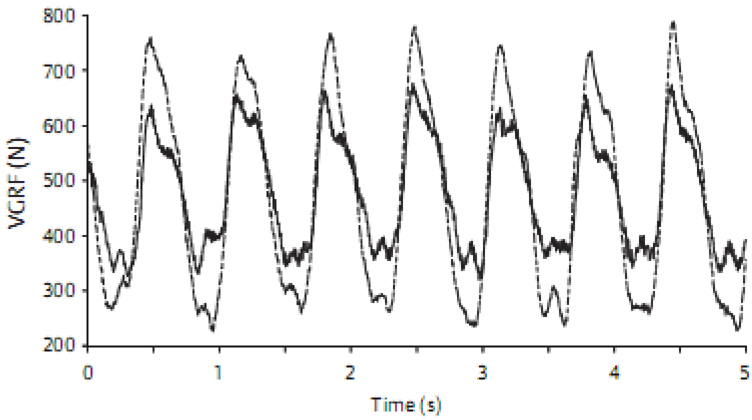

Figure 2.7: VRGF from right leg of a grinder between normal (- - -) and splinted (—) grinding [18].

From the cardiorespiratory response test employing an online breath-by-breath gas analysis system, compared to normal grinding, knee joint splinted grinding elicited a higher cardiorespiratory response containing CO_2 production (VCO_2), minute ventilation (VE), heart rate (HR), respiratory exchange ratio (RER) and blood lactate concentration (4.8 ± 0.8 mmol·L^{-1} for splinted grinding and 3.7 ± 1.0 mmol·L^{-1} for normal grinding) but no remarkable change in O_2 production (Table 2.3), which caused a significant increase in physiological stress and a tendency to anaerobic metabolism. During splinted grinding, a higher proportion of work that needed more energy for muscles was done by upper body. Except for lactate, the additional energy was largely supplied by anaerobic metabolism. The work done by upper body muscles turned out to be less efficient at oxygen conductance than leg muscles, which might result in an increased anaerobic metabolism. The reduced capability of extracting oxygen by the upper body might also require cardiorespiratory effort to complete the task. Furthermore, the upper body had a higher tendency to produce lactate but hardly used it than the lower body. To balance production and removal of lactate and reduce physiological strain, it was recommended to make dynamic use of legs instead of keeping them restricted during grinding. In contrast, seated cranking which imposed dynamic restrictions on lower limb, grinders could perform better while standing [6] [18], although it has been proved in one article that the type of arm cranking did not influence the maximum cardiorespiratory response [20].

	Work Rate (W)	VO_2 ($L \cdot min^{-1}$)	VCO_2 ($L \cdot min^{-1}$)	RER	V_E ($L \cdot min^{-1}$)	HR ($beats \cdot min^{-1}$)
normal	246 ± 14	4.1 ± 0.2	4.1 ± 0.3	1.01 ± 0.06	129 ± 18	165 ± 13
splinted	246 ± 13	4.0 ± 0.2	4.5 ± 0.3*	1.12 ± 0.10*	151 ± 18*	172 ± 12*

*Significantly greater than Normal ($p < 0.001$), Mean ± SD, $n = 8$

Table 2.3: Cardiorespiratory responses between normal and splinted grinding [18].

2.6 System resistance and deck heel

In the real race, system resistance (the load on the winch) and deck heel (tilt) which are products of wind strength and yacht heading can also affect grinding performance [2] [9][21]. On one hand, high system resistance is usually regarded as a more important factor to on-water performance [11]. For both forward and backward grinding, performance becomes more variable as resistance increases. On the other hand, when sailing upwind the system resistance and deck heel (up to 25-30°) increase and vice versa. Grinding on flat condition is more reliable than in tilted condition, which implies the standard error of the mean (SEM) is higher for tilted condition than that in flat condition grinding in the research [9].

Between two types of deck heel, anterior-posterior heel and left-right heel, the performance is more variable for left-right heel than anterior-posterior heel in paired grinding [11]. The height of pedestal is changeable due to the sailor position in anterior-posterior tilt, which results in an alteration in basic line of the motion during the push phase for forward grinding and the pull phase for backward grinding.

2.7 One- repetition maximum

One-repetition maximum (1 RM) is the maximum amount of weight one can lift in a single repetition. It can be used to determine the maximum strength for upper body which might be important for grinding performance. Approximate 1RM can be calculated by the formulae $1\ \mathrm{RM} = [\left(\frac{\mathrm{r}}{30}\right) + 1] \cdot \omega$ or $1\ \mathrm{RM} = \omega \cdot \frac{36}{(37-\mathrm{r})}$ which returns a slightly lower maximum for fewer than 10 repetitions, where 1 RM means one repetition maximum, ω represents weight lifted and r stands for repetitions completed. Completed 4-6 RM predicts more accurate result than 7-10 RM [22].

Grinding against moderate and heavy resistances, bench press 1 RM and maximum force capability separately have strong relationship with forward grinding performance (r=0.88-0.99 and 0.87-0.99), the relationship rises when grinding load increases. Bench pull 1 RM, maximum power and maximum force respectively show strong relationship with backward grinding performance (r=0.90-0.95, 0.85-0.98 and 0.87-0.95) [11].

Since muscular power, the product of force and velocity is used to measure the performance in some sports. The relationship between muscular power and 1 RM was examined in a research [11]. The range of loads of the test was determined as 10-100 % of 1 RM with 10 % intervals. From the following chart (Figure 2.8), power was similar for two grinding directions at 10 % of 1 RM, but it increased more with increasing loads for backward grinding than forward grinding. Muscular power output was maximized at loads of 53.3 ± 1.7 % and 49.7 ± 4.4 % of 1 RM for mean and peak power in forward grinding and 78.6 ± 5.7 % and 70.4 ± 5.4 % of 1 RM respectively in backward grinding.

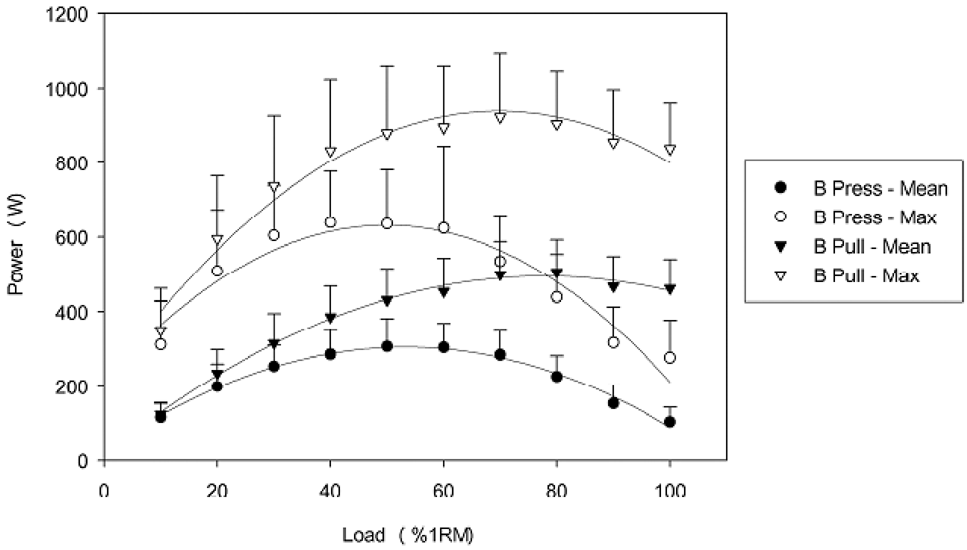

Figure 2.8: The power load spectrum for forward and backward grinding [11].

2.8 Determinants of grinding performance

One study [13] investigated that the kinetic and kinematic characteristics of bench press and bench pull exercises could be used to give tips to grinding training.

The relationships between these interested variables of 1 RM, maximum force, maximum velocity, maximum power, the load at maximum power and grinding performance are shown in Table 2.4 and 2.5. For forward grinding (Table 2.4), 1 RM and max force had high correlation with grinding, but a stronger relationship to heavy load grinding than that to moderate load grinding. Max velocity had no significant correlation with grinding performance. Max power and max power load did not have tight relationship to performance either; however, max power positively associated grinding performance while max power load did in the opposite. For backward grinding (Table 2.5), 1 RM and max force still correlated to grinding performance in a large extent. Differently, velocity capability showed a great relationship with heavy load grinding although a relatively slight relationship with moderate grinding. Max power generated a remarkable correlation with both grinding conditions whereas stronger correlation happened to heavy load grinding. Max power load had a similar situation in backward grinding compared to forward grinding.

The overall results in forward and backward grinding performance indicated that 1 RM was the key predictor for both directions and both load conditions. Max power was deemed as a significant factor in backward grinding but negligible in forward grinding. It could be attributed to difference in muscle architecture between extensor muscles and flexor muscles.

It appeared that the training for the sailors should focus on improving maximum force generation. It could be recommended to incorporate great velocity or max power component on the basis of maintaining maximum force in backward grinding training in order to develop maximum force.

Variable	Mean (*SD*), $n = 11$	Correlation with moderate load (*p*)	Mean (*SD*) $n = 6$	Correlation with heavy load (*p*)
1RM (kg)	119.7 (23.9)	0.88 (0.000)	133.7 (23.8)	0.99 (0.000)
Max force (N)	1176.3 (232.0)	0.87 (0.000)	1311.3 (233.2)	0.99 (0.000)
Max velocity (m/s)	0.95 (0.14)	−0.03 (0.940)	0.95 (0.18)	0.18 (0.734)
Max power (W)	304.7 (68.6)	0.55 (0.081)	323.7 (89.5)	0.49 (0.326)
Pmax load (%1RM)	53.3 (1.7)	−0.47 (0.142)	52.8 (2.1)	−0.54 (0.264)

*1RM = 1 repetition maximum; Pmax = maximum power.
†Mean and *SD* shown for independent variables and Pearson correlations with associated *p* values indicate relationship with performance.

Table 2.4: Relationship between variables and forward grinding [13].

Variable	Mean (*SD*) $n = 11$	Correlation with moderate Load (*p*)	Mean (*SD*) $n = 6$	Correlation with heavy Load (*p*)
1RM (kg)	99.4 (15.4)	0.90 (0.000)	107.0 (16.3)	0.95 (0.000)
Max Force (N)	983.9 (146.7)	0.87 (0.000)	1049.4 (159.7)	0.95 (0.004)
Max Velocity (m/s)	1.20 (0.16)	0.56 (0.074)	1.22 (0.20)	0.97 (0.001)
Max Power (W)	499.1 (87.0)	0.85 (0.001)	539.8 (96.7)	0.98 (0.000)
Pmax load (%1RM)	78.6 (5.7)	−0.34 (0.311)	77.6 (5.3)	−0.45 (0.372)

*1RM = 1 repetition maximum; Pmax = maximum power.
†Mean and *SD* shown for independent variables and Pearson correlations with associated *p* values indicate relationship with performance.

Table 2.5: Relationship between variables and backward grinding [13].

2.9 Grinding systems

There are two types of grinding systems [11], conventional system where the pedestal is orientated left-right tilt and in-line system where the pedestal is anterior-posterior tilt when grinding under deck heel conditions (Figure 2.9). It has been concluded from the grinding performance tested in previous studies [11] [23] that grinding in a flat condition basically showed good performance both in conventional and in-line systems. The in-line system had a better performance than that of conventional system under all handle speeds and load conditions especially for heavier loads based on two sailors paired experiments. However, for one subject grinding test, grinding in conventional system was slightly better but no significant difference between two systems.

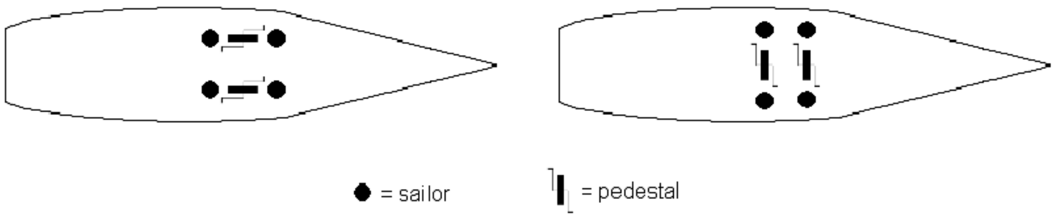

Figure 2.9: Conventional (left) and in-line (right) systems for pedestals [11].

2.10 Crank arm length and crank-axle height

Other important factors affecting grinding are crank arm length and crank-axle height. The following content is based on the study of influence of crank arm length and crank-axle height on standing arm cranking [4]. The grinders were required to perform duration of 6 s maximum effort sprints separated by 10 min rest interval. It was completed at four variable crank am lengths (16.2, 19.9, 23.6 and 27.3 cm) with a certain crank-axle height of 105 cm and four variable crank-axle heights (85, 95, 105 and 115 cm) with a fixed crank arm length of 25 cm.

The relationship between crank arm length and crank-axle height with peak power fit for quadratic polynomial. The curves (Figure 2.10 and 2.11) shows the highest peak power occurred at the crank arm length of 12.3 % of arm span and at the crank-axle height of 57.3 % of stature. The quadratic polynomial observed for peak power with crank arm lengths and crank-axle heights could due to interactions among torque, crank speed and posture. These variables should be taken into consideration to design the grinding pedestal. It suggested the optimum values of crank arm length and crank-axle height are respectively 12-12.5 % of arm span and 50-60 % of stature. When the crank-axle height was below 50 % of stature, grinding performance significantly decreased. Grinding at a low crank-axle height (Figure 2.12) below 50 % of stature, the hip flexion and the load on low back increased, which resulted in a high risk of injury for grinders [3-5].

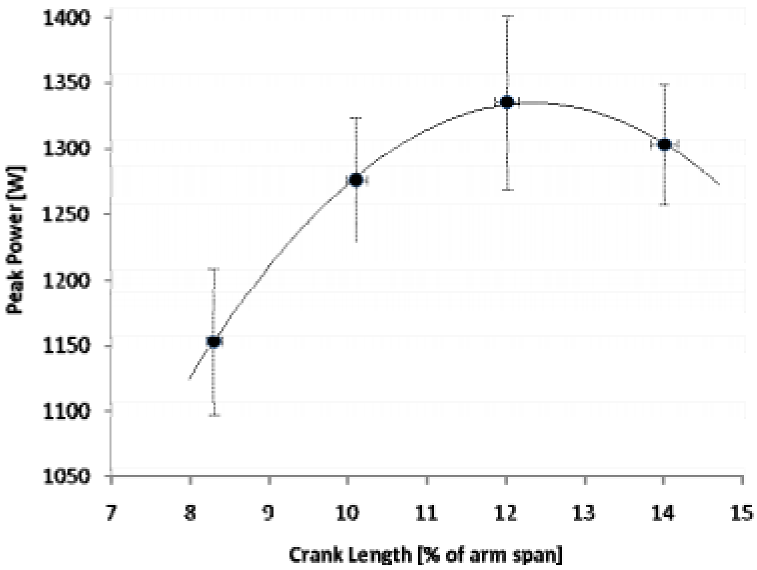

Figure 2.10: Relationship between peak power and crank arm length (% of arm span) [4].

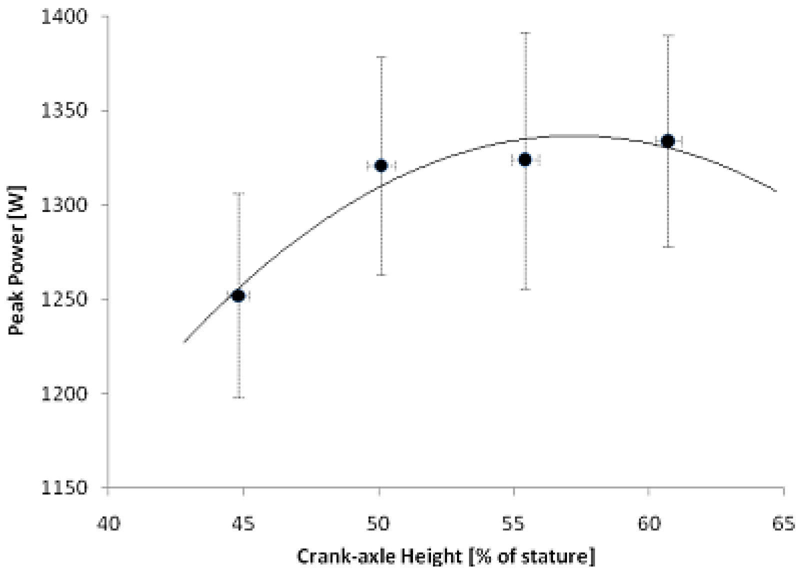

Figure 2.11: Relationship between peak power and crank-axle height (% of stature) [4].

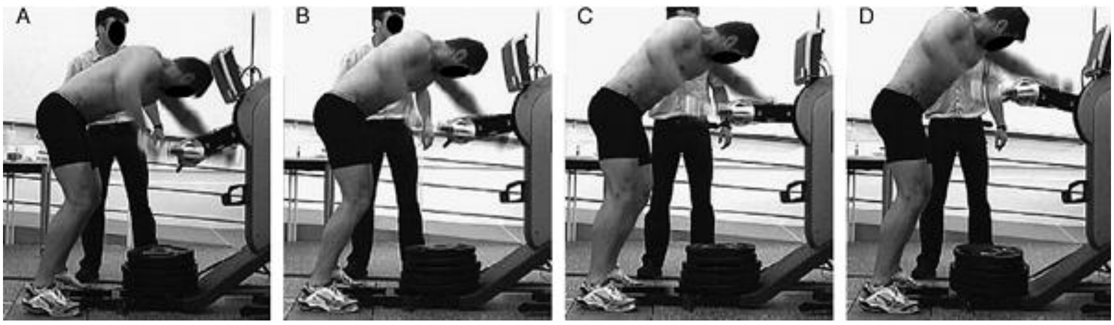

Figure 2.12: Grinding at different crank-axle heights (A, 85 cm; B, 95 cm; C, 105 cm; D, 115 cm) [4].

2.11 Recovery from grinding

One study [24] based on physiological characteristics of America's Cup sailors mentioned rest interval during grinding movement. In the real race, the grinder had to recover so quickly that the body needed fast oxygen supply and high anaerobic fitness. High aerobic fitness allowed the time of setting sails to get reduced. Anaerobic energy was replenished during fast recovery to prepare for the following grinding activity. Figure 2.13 illustrates an example of oxygen uptake (VO_2) and heart rate (HR) recordings during one tacking grinding activity. It recorded 13 s of tacking beginning from the time when grinders reached revolution speed of 120-150 rpm plus about 4 min after the tacking. From this curve, in the first phase, VO_2 climbed up to the top; VO_2 declined sharply in the second phase; and the third phase showed a slow decrease in VO_2. Heart rate gave a similar result as that of VO_2. In order to have a relatively adequate rest interval without cooling down the body, 3-5 min of rest between trials in the experiment is acceptable and feasible.

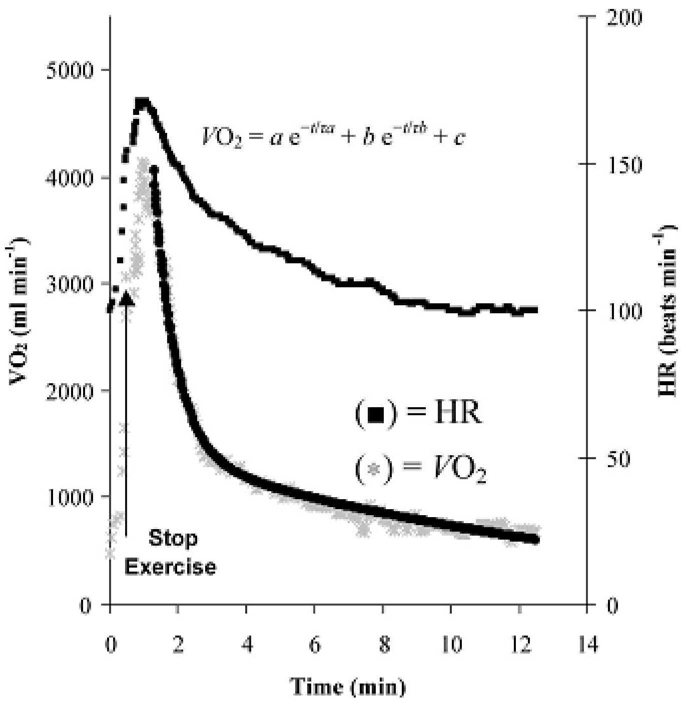

Figure 2.13: Heart rate (HR, ■) and oxygen uptake (VO_2, ×) in one tacking performance [24].

2.12 Assessment of grinding performance

Two main assessments of grinding performance are used in research. Power output is defined as a product of the applied force (F), the length of crank arm (L) and the angular velocity (ω). The first one is peak power which has been considered as a valid assessment of grinding performance reflects the fastest speed performed in an observation period. Besides, external work which means the integration of power for a certain grinding time is calculated for example by means of the sum of power for 5 s after the peak power occurs within an 8 s grinding duration. The standard error of the mean (SEM) defined as standard deviation of the sample mean estimate of a population mean are used for analysis. In one study [9], the reliability of forward and backward grinding performance under a range of system resistance and deck heel was tested.

In system resistance test, three loading conditions 39 N·m (Light), 48 N·m (Moderate) and 68 N·m (Heavy) were examined for both forward and backward grinding. All the 18 sailors accomplished light and moderate load conditions and 6 primary sailors completed heavy load condition. All trials were in the maximal effort of eight seconds and separated by 3-5 min rest. The equipment was set up with standard crank-axle height of 87 cm and crank arm length of 25 cm.

In deck heel test, 9 subjects performed forward and backward grinding in five tilted conditions: flat, 0°; downhill, grinding at 25° deck heel above the pedestal; uphill: grinding at 25° deck heel below the pedestal; right: grinding at 25° deck heel with high pedestal at right side and left: grinding at 25° deck heel with high pedestal at left side. All ten conditions were completed against a constant load of 45 N·m.

The result of system resistance test shows in Table 2.6. The SEM between peak power and external work were 1.3-5.4 % and 1.6-3.9 %, and the average were separately 3.3 % and 3.1 %. The SEM inclined to increase as the loads ascended for both grinding directions, which implied that performance became variable while increasing the load.

Grinding condition	Test 1	Test 2	M_{diff}	SEM	ICC
Peak power (W)					
Back – Light 39 N·m	650 ± 51	673 ± 58	− 0.1%	1.3%	0.98
Back – Moderate 48 N·m	609 ± 135	604 ± 132	− 0.7%	3.1%	0.98
Back – Heavy 68 N·m	796 ± 134	797 ± 112	0.4%	4.2%	0.93
Forward – Light 39 N·m	722 ± 59	729 ± 55	1.1%	1.6%	0.96
Forward – Moderate 48 N·m	697 ± 140	683 ± 136	− 2.1%	4.2%	0.96
Forward – Heavy 68 N·m	913 ± 128	929 ± 100	2.1%	5.4%	0.84
External work (kJ)					
Back – Light 39 N·m	90.3 ± 6.2	94.2 ± 8.9	− 0.5%	1.6%	0.96
Back – Moderate 48 N·m	79.5 ± 16.6	79.5 ± 16.9	− 0.2%	3.9%	0.97
Back – Heavy 68 N·m	108.3 ± 16.1	109.5 ± 16.1	1.2%	3.7%	0.95
Forward – Light 39 N·m	100.9 ± 8.4	101.5 ± 8.5	0.7%	2.6%	0.91
Forward – Moderate 48 N·m	88.3 ± 17.2	89.9 ± 17.9	1.1%	3.5%	0.97
Forward – Heavy 68 N·m	124.2 ± 16.5	125.8 ± 13.7	1.5%	3.7%	0.92

Table 2.6: Peak power and external work for grinding performance during different load conditions [9].

The result of heel deck test shows in Table 2.7. The SEM between peak power and external work were 3.5-9.6 % and 4.6-6.9 %, and the average were 6.1 % and 5.5 % respectively. It was remarkably higher in right-left tilt than uphill-downhill tilt for both peak power and external word as assessment. The stability generally reduced while shifting from flat to tilted condition, which resulted in variable performance.

Grinding condition	Test 1	Test 2	M_{diff}%	SEM%	ICC
Peak power (W)					
0° – Back	635 ± 231	620 ± 239	3.3	6.1	0.97
25° – Back, Downhill	559 ± 181	533 ± 157	−4.1	5.9	0.96
25° – Back, Uphill	612 ± 237	625 ± 234	2.6	5.0	0.98
25° – Back, Right	587 ± 196	593 ± 197	1.0	9.6	0.92
25° – Back, Left	617 ± 227	604 ± 202	−1.0	6.8	0.96
0° – Forward	717 ± 292	719 ± 282	0.6	6.1	0.98
25° – Forward, Downhill	656 ± 230	681 ± 264	2.6	4.3	0.99
25° – Forward, Uphill	702 ± 290	734 ± 312	3.9	3.5	0.99
25° – Forward, Right	662 ± 245	677 ± 229	1.6	7.5	0.96
25° – Forward, Left	680 ± 251	684 ± 267	0.0	6.0	0.98
External work (kJ)					
0° – Back	81.4 ± 32.7	80.1 ± 30.6	−0.9	4.6	0.99
25° – Back, Downhill	68.7 ± 23.5	68.6 ± 22.7	0.2	5.0	0.98
25° – Back, Uphill	78.3 ± 29.9	80.7 ± 32.2	2.4	4.7	0.99
25° – Back, Right	74.0 ± 23.8	76.5 ± 27.5	2.3	5.8	0.97
25° – Back, Left	81.0 ± 30.3	77.7 ± 26.2	−3.0	6.8	0.97
0° – Forward	90.8 ± 37.5	90.6 ± 35.1	0.6	4.8	0.99
25° – Forward, Downhill	84.6 ± 28.5	89.9 ± 35.2	4.3	4.8	0.98
25° – Forward, Uphill	90.6 ± 34.6	93.7 ± 40.9	1.2	5.9	0.98
25° – Forward, Right	86.6 ± 31.5	89.5 ± 36.3	1.8	6.9	0.97
25° – Forward, Left	84.7 ± 30.5	86.2 ± 33.9	1.0	5.7	0.98

Table 2.7: Peak power and external work for grinding performance during different tilt conditions [9].

Overall, it appears that there is difference in reliability between peak power and external work when system resistance and deck heel are varied, especially when deck heel is involved, peak power is less reliable. External work is more appropriate and reliable to assess grinding performance than peak power, because maintaining power output over a period of time with regard to muscular force endurance should be taken into account [9] [25].

Therefore it can be considered external work as a more appropriate assessment of grinding performance, which is because the external work corresponds to the total amount of work done in a certain period [9] [26]. However, the variation was observed high with heavy load compared with light load, which could result from fewer subjects completed the trials at heavy loads than light loads. The low statistical power connecting to low subjects led to a higher SEM. Besides, physiological and mental fatigue and long testing session could also affect the reliability of performance [26].

Chapter 3
Problem formulation

This chapter firstly demonstrates the limitations of previous study, and then through these disadvantages, what should be avoided and improved in this research is referred. Finally it focuses on the formation of hypothesis.

3.1 Limitations of previous studies

The main parameters of a grinding pedestal are crank-axel height and crank arm length (do not take changeable resistance and deck heel into account in laboratory environment), which have been respectively reported the optimum ranges are of 50-60 % of stature and 12-12.5 % of arm span [4]. This conclusion is based on the relationship between peak power with crank-axel height and crank arm length; however, external work, the integration of power for a certain period, is deemed as a more appropriate assessment of grinding performance than peak power. The reason is that the external work corresponds to the total amount of work done in that duration, which accords with the conclusion that occurrence of peak power and power maintenance of upper body are influential factors in forward grinding [3]; whereas peak power relating to the maximum power obtained in that period, which only takes the time when the maximum power appears into consideration, could not be enough.

The standard value of crank-axle height of 87 cm and crank arm length of 25 cm are in use in the real race. The average height of 30 grinders who sailed for top three teams during the 32nd America's Cup was 188 cm [6], which means the standard crank-axle height accounts for 46.28 % of stature and the crank length occupies 13.3 % of arm span. Apparently, they are not at the optimum ranges of 50-60 % of stature or 12-12.5 % of arm span but still in use. Whether these standard values are the optimum ones for grinding activity should be verified in a further step.

Three torque load conditions: 39 N·m (light), 48 N·m (moderate) and 68 N·m (heavy) were used in tests [25]. However, subjects perform quite differently on these fixed loading values. For instance, it could be very easy for a strong subject to grind against the light loading condition compared to a subject who has relative weak upper body. Such as the research on the optimal crank-axle height and crank am length, those fixed loading conditions result in different levels of grinding performance for different subjects, which could be considered as a variable, even though the recruited subjects were probably in the same arm span and height, there is no doubt that some bias may occur in the results. The problem can be solved if the individual loading condition is used.

It is reported that bench press 1 RM is a suitable predictor of forward grinding performance [22]. Mean power output is maximized at loads of 78.6 ± 5.7 % of 1RM for bunch pull and 53.3 ± 1.7 % of 1 RM for bench press respectively. Peak power output is maximized at loads of 70.4 ± 5.4 % of 1 RM for bunch pull and 49.7 ± 4.4% of 1 RM for bench press separately [11]. This could imply a method to solve the issue of individual testing resistance. However, bench press and bench pull 1

RM separately have strong relationship with forward and backward grinding (r=0.88-0.99 and 0.90-0.95), where the relationship between grinding performance and the examined percentage of loads inducing maximum mean or peak power is not clear. Since this percentage of 1 RM is tested under the activity of lift not grinding which equals arm cycle exercise, whether this percentage of 1 RM is a properly individual loading condition of grinding is not proved.

3.2 Hypothesis

The purpose of this study is to investigate the optimal crank-axel height and crank arm length with external work as the assessment of grinding performance and determine the combination of crank-axel height and crank arm length for enhancing performance. As it reported, the optimal values are of 50-60 % of stature and 12-12.5 % of arm span with peak power as the assessment of grinding performance. However, the duration of power output after the occurrence of peak power is also important to the performance, which means it is possible to have a deceased power output after the occurrence of peak power so that only peak power cannot identify this change in power output. In this case, external work could be very different from peak power to assess grinding performance. When applying external work as the assessment, the optimal ranges of crank-axel height and crank arm length could vary compared to that using peak power as the assessment.

Chapter 4

Problem solving

This chapter mainly concentrates on the outline of experiment design and data analysis to solve the problem of determination of optimum crank arm length and crank-axle height.

4.1 Requirement

In order to achieve the purpose of this study, software code and equipments which match experiment protocol are invented. Matlab code mainly focuses on the calculation of angular velocity and external work; equipments design achieved by Solidworks program concentrates on a new handle design covering the range of crank arm length. The details are demonstrated in the following paragraphs.

4.2 Experiment design

4.2.1 Introduction

The aim of the experiment is to investigate the optimal crank-axel height and crank arm length with the external work as the assessment of grinding performance and determine the combination of crank-axel height and crank arm length for enhancing performance. The optimal ranges are of 50-60 % of stature and 12-12.5 % of arm span with the peak power as the assessment of grinding performance have been reported in the previous studies. The improvement of this study is based on external work as performance assessment instead of peak power, which probably causes a shift of the optimum ranges because peak power only implies the maximum power and when it happens, in comparison, external work suggests both when peak power appears and how long high power is retained. Although in the experimental setting, deck heel and changeable resistance are neglected. The result of this study could provide a suitable combination of crank-axel height and crank arm length as the result of generation of great performance.

4.2.2 Methods

The equipment setup is the crank-axle height range of 87, 92, 97, 102, 107 and 112 cm (standard 87 cm) and the crank arm length range of 17.5, 20, 22.5 and 25 cm (standard 25 cm). Since it has been reported that grinding under 50 % of stature did harm to low back [3-5], which is the main reason to start the testing crank-axle height from 87 cm, plus one study [4] concluded the optimum crank-axle height was 50-60 % of stature, this is the base how the crank-axle height range is determined. The reason that the testing crank arm length stops at 25 cm is due to the limited travel space of the handle derived from the shape of grinding machine. The distance between two centers of handles in the experiment is 36 cm, a little shorter than standard of 48 cm.

The test is performed with a total body trainer (Figure 4.1) with removal of seat and feet pedals. Besides, there are some parts needed to be fixed. It is 104 cm high from the ground to the hub, which is not able to satisfy the changeable range of rank-axle height, the way to solve this problem could be adding some platforms and footplates to increase or reduce the distance between the hub of rotation and feet of subjects. The crank arm length is too short to fit the crank arm length variation in the experiment. Moreover, the handles should be straight and vertical to crank arm.

Figure 4.1: Total body trainer

The data is exported from body trainer to the computer with DAQ card attached. There are two s of signals originating from the training machine and transferring to the DAQ card via cables and interfaces. The channels are plugged in the input interfaces (Figure 4.2). The voltage of 5 V is needed to drive the data export, so that two wires are connected to the interface of 5 V and the ground (Figure 4.3). The software called Kick (Figure 4.4) is applied to display and record the data which is used to estimate external work afterwards.

Figure 4.2: Interfaces connection.

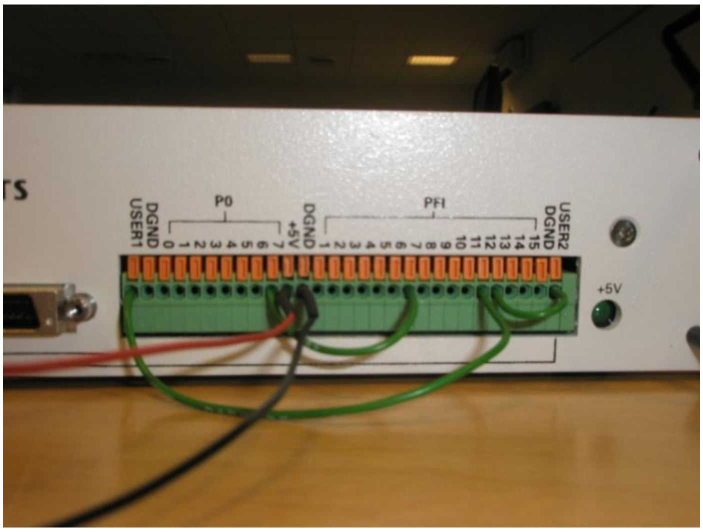

Figure 4.3: Voltage and ground connection.

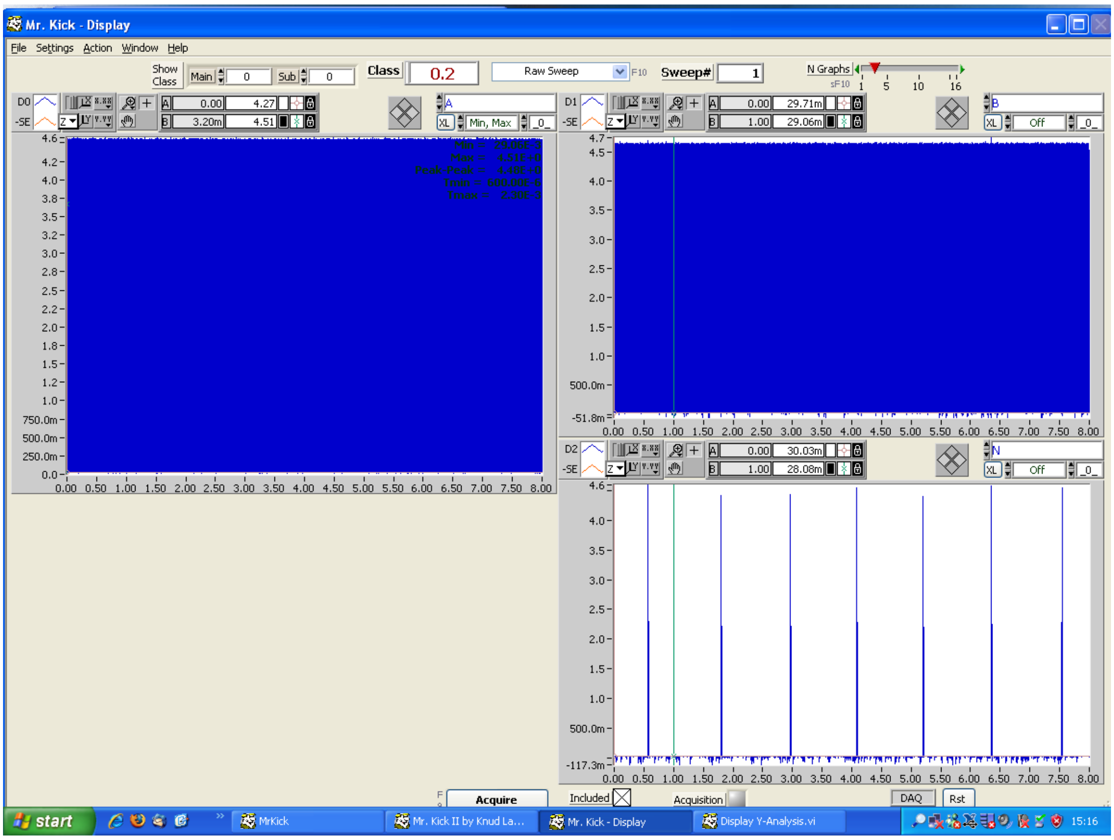

Figure 4.4: User interface of Kick software

The cable marked N symbolizes the judgement of the revolutions (graph at lower right corner in Figure 4.4). The sampling frequency is 10000 Hz, which is to assist the system produce a high amplitude pulse if the left handle reaches the highest point vertical to ground. The duration of one intact revolution symbolizes the time between two continuous pulses. The cable marked A means that it displays all the pulses during the continuing arm-cranking (graph at upper left corner in Figure 4.4). There are a certain number of pulses in one intact revolution. The angle of rotation is fixed between pulses. It hits the peak voltage when the handle passes through the certain angle of rotation.

4.2.3 Procedure

First of all, the anthropometric characteristics including height, weight and arm span are measured for recruited male subjects. At the given resistance of level 10, all the subjects have to perform an 8 s standing forward grinding with maximum effort at each combination of crank-axle height (87, 92, 97, 102, 107 and 112 cm) and crank arm length (17.5, 20, 22.5 and 25 cm) after self warm up. In total, every participant performs 24 trials which lasts maximum 2.5 hour. There is 5 min rest interval between trials. A verbal 3 s countdown is given to help subjects focus.

4.2.4 Data analysis

The external work is calculated by the sum of 5 s duration of power output starting at the occurrence of peak power. Based on the relationship between angular velocity (ω) in rad/s and power (p) in watts, the detection to occurrence of peak power is equal to the occurrence of peak angular velocity. Plus power can be calculated from the function of power and angular velocity at every single sample, the external work which is the product of power and time is able to be deduced.

In the analysis of the optimum crank-axel height, a relationship between external work and crank-axle height (% of stature) is examined based on one certain crank length (25 cm). Each subject has 6 trials for different crank-axel heights at the crank length of 25 cm. The relationship is assumed parabola and plotted individually for each subject. The intersection for all individual optimum ranges is deemed as the overall optimum crank-axel height.

The similar method is applied in the analysis of the optimum crank arm length, a relationship between external work and crank arm length (% of arm span) are portrayed grounded on a certain crank-axle height (87 cm). Participants complete 4 trials individually. The relationship is considered parabola as well. The intersection is used again to obtain the optimum crank arm length.

In addition, to analyze the optimum combination of crank-axle height and crank arm length, 3D curves among external work, crank-axle height (% of stature) and crank arm length (% of arm span) are plotted individually, and then intersection is applied. Another 3D figure based on the data of all the subjects together is drawn to testify the intersection.

Chapter 5
Equipment design

According to the protocol of experiment, the equipment requires to be designed. A pair of handles, a pair of crank arms, some footplates and platforms is required. All the edges and corners of newly made equipments are needed to be polished smoothly due to safety. Moreover, skidproof material is also needed to wrap footplates to avoid feet going into a skid and guarantee similar friction.

5.1 Handle and crank arm

The old bent handle is needed to be removed completely. The new handle (Figure 5.1) should be rotatable, straight and vertical to crank arm. The shape of the handle is cylinder. The diameter of handle is 3.5 cm and the length is supposed to be 24 cm. The center of handle is 2.5 cm away from the end of crank arm.

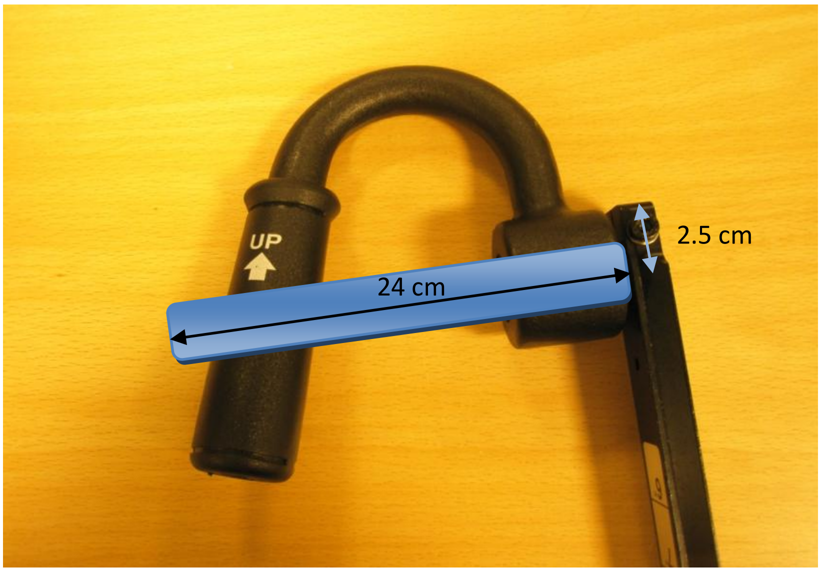

Figure 5.1: The blue column shows the new handle.

The crank arm should be shaped as exactly same as the original one except for the grooves which is demonstrated below in the picture (Figure 5.2). Four grooves whose distances from the center to the center of hub are respectively 17.5, 20, 22.5 and 25 cm. The distance between the furthest groove away from the center of hub and the end of crank arm is 5 cm.

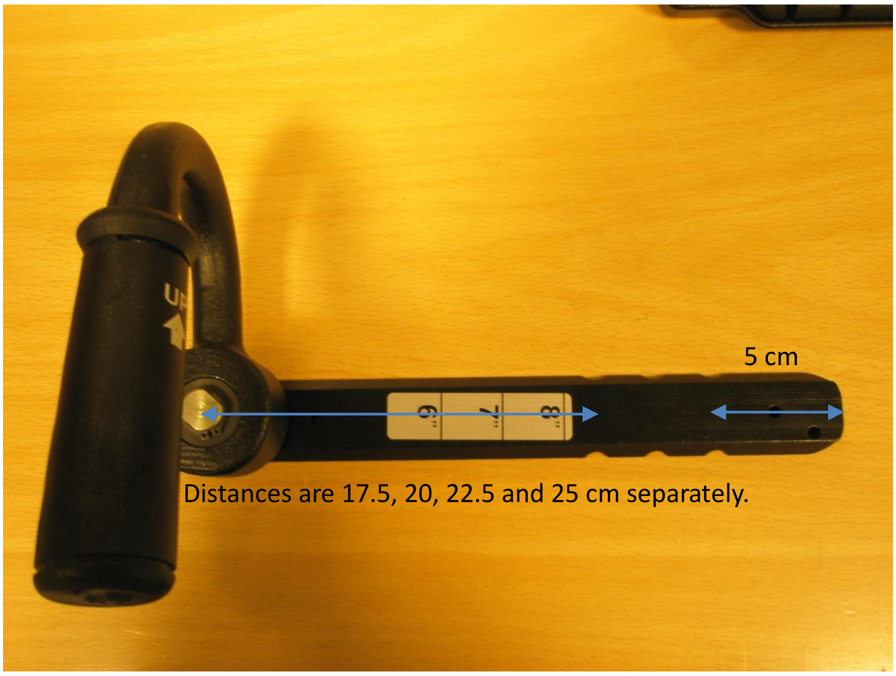

Figure 5.2: Crank arm

The SolidWorks software is responsible to build these handle and crank arm. The finished product is shown in Figure 5.3 with a rotatable handle and a changeable length crank arm. The details of the process are presented in Appendix A.

Figure 5.3: SolidWorks sketch of handle and crank arm.

5.2 Footplate and platform

The distance between hub and ground is 104 cm (Figure 5.4). It needs footplates with heights of 17, 12, 7 and 2 cm and platforms with heights of 3 and 8 cm to individually decrease and increase the distance between hub and feet. The footplates are cut into the size of 40 cm length and 30 cm width and wrapped with the same skidproof material. The platform for the front side is at least in a size of 80 cm length and 30 cm width to cover the size of the pedestal of machine. The one for the other side is minimal in a size of 35 cm length and 30 cm width to carry the seat of the machine which is sat by one subject to increase the stability of machine during grinding.

In experiment, the distance between hub and feet of 112 cm is implemented by carrying the machine by 8 cm; the distance of 107 cm is executed via lifting the machine by 3 cm; the distance of 102 cm is achieved through putting 2 cm footplates underneath the feet and the rest can be done in the same manner.

Figure 5.4: Figures of body trainer.

Chapter 6

External work calculation

External work, the assessment of grinding performance, plays an important role in data analysis. The factors of external work calculation are instantaneous angular velocity, power output and time. This chapter elaborates on the method of external work calculation.

6.1 Instantaneous angular velocity calculation

In order to calculate instantaneous angular velocity which is used to estimate the power output and external work afterwards, Matlab code is applied to accomplish this goal (Appendix B). In general, the first step is to obtain the amount of pulses from Channel A for each intact revolution; secondly, confirm time difference between the starting points of two adjacent pulses by calculating the number of samples from Channel A; thirdly, since the amount of pulses for each revolution is supposed to be a fixed value, the rotational degrees between pulses is calculated by the method that 2π divide by the amount of pulses for one intact revolution and finally, using the degree obtained from the third step to each divide the time difference got from the second step to gain the instantaneous angular velocity all over the intact revolutions.

In the first place, the number of intact revolutions detected in Channel N is shown in Figure 6.1, which is the number of peaks minus one. Through reading how many samples between the first and last peaks, the time expense is obtained by the amount of samples divide by sampling frequency. The x axis represents sample and the y axis stands for voltage. All the rest of signal processing part is based on the data from Channel A (Figure 6.2 and 6.3) corresponding to those revolutions found in Channel N. The achievement basically relies on the counter, which means that since the sampling rate is quite high, the samples of voltage (y axis) (samples at x axis) reach either peak or bottom. The mean value can be set as the threshold. Input value one when it hits the peak or value zero when it gets to the bottom in an array. The way to count how many peaks in Channel A is to count the total number when the value jumps from zero to one. The method to specify the time difference between peaks in Channel A is similar with the way to calculate the amount of peaks. After gaining all the values of zero and one, plus the beginning of each peak is already known, the calculation of value jump changes into how many zeros and ones in total between the start of two adjacent peaks. Since the distance is constant between peaks, the zeros and ones which stands for the time difference is countable, and then the division that distance divides by time difference is the result of instantaneous angular speed.

The following three graphs are original from a grinding trial in generally constant speed. From Channel A, the amount of pulses in one revolution is 2048 obtained from Matlab program, which also means the angle of rotation between equals $2\pi/2048$.

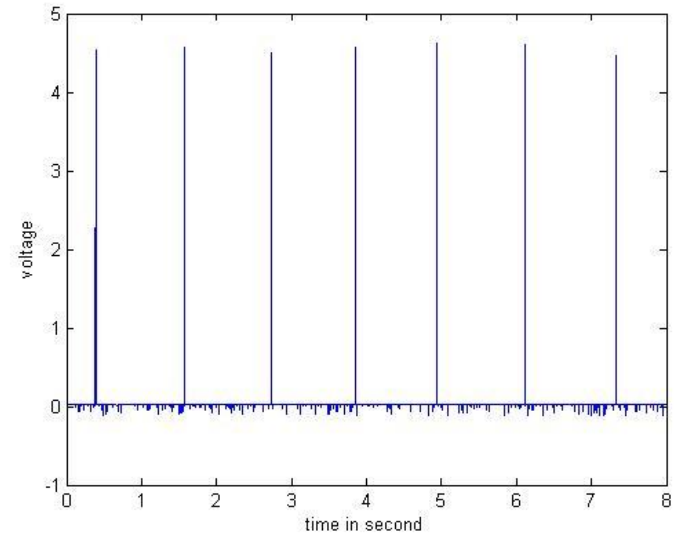

Figure 6.1: Channel N.

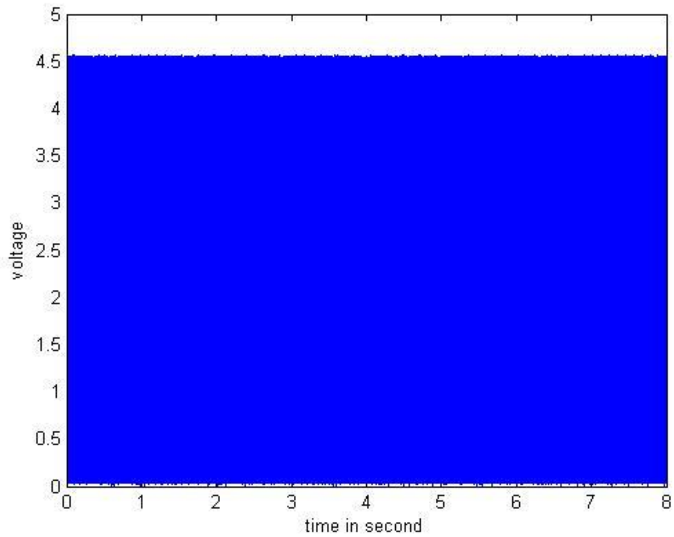

Figure 6.2: Channel A.

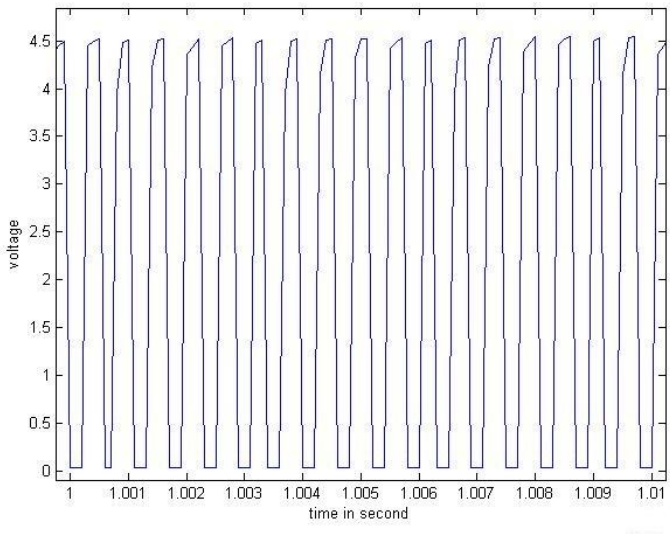

Figure 6.3: Partial zoom-in of Figure 6.2.

After plotting angular velocity between two pulses, interpolation is applied to supplement missing instantaneous angular velocity. Since the low frequency contains required information from Fourier transform (Figure 6.4), the amplitude of 0-1 Hz touches the maximum amplitude that equals to one, where the rest of frequencies have extremely low amplitude. An order three low pass Butterworth filter with cutoff frequency 1 Hz is designed to get rid of noises from the pure angular velocity signal.

Two plots (Figure 6.5 and 6.6) separately show angular velocity in condition of constant velocity grinding and maximal effort grinding against the resistance of level 10. Although it fluctuates quite a bit in Figure 6.5, it still shows the average speed is around 5.5 rad/s. In Figure 6.6, the curve climbs up to the top at about Second 2 after starting grinding and then it declines gradually.

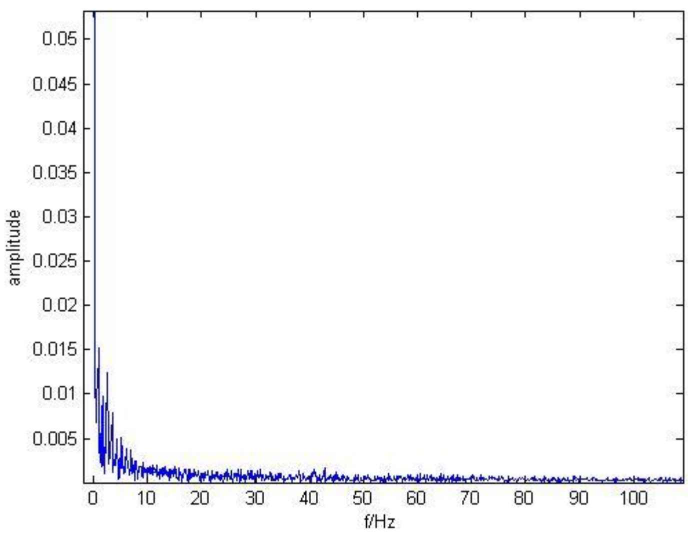

Figure 6.4: A zoom-in graph of Fourier transform of angular velocity.

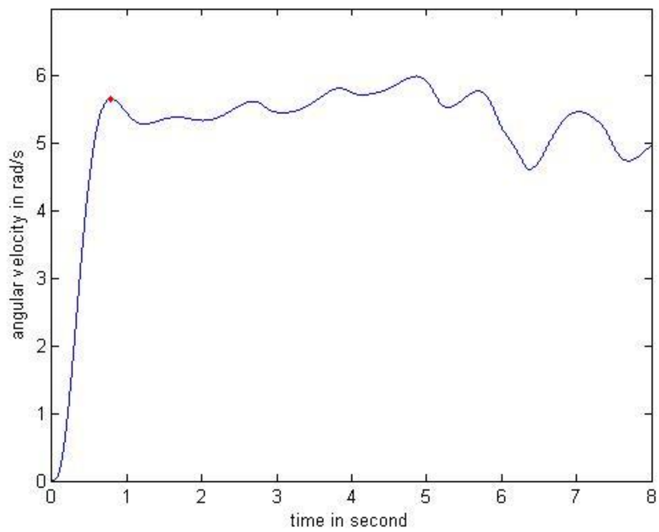

Figure 6.5: Angular velocity with a constant grinding speed.

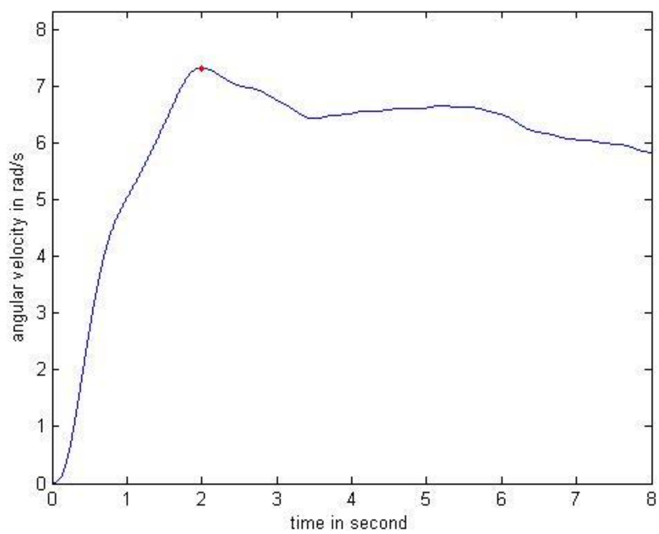

Figure 6.6: Angular velocity with maximal effort

6.2 System calibration

According to the power displayed on the screen of the training machine, the formula that power is the product of the torque τ (product of applied power and distance) and angular velocity ω in rotational system, which is written $\mathrm{P(t)} = \tau \cdot \omega$, where ω is measured in radians per second. In the testing level, asking the subjects to perform constant speed cranking for a certain time (8 s) at different power outputs, then the relationship between power and angular velocity is able to be plotted. The only unknown value in the formula is τ. It is assumed that τ is subject to change as the level changes. A curve between power and angular velocity is required to plot to illustrate the characteristic of the level whether or not linear. After plotting the dots of angular velocity regarding each power output the subject maintained, a method of polynomial fit is applied to estimate the relationship between power and angular velocity. In order to judge how good the goodness of polynomial fit, the coefficient of determination R^2 is calculated by a formula $R^2 = 1-(\frac{SS_{err}}{SS_{tot}})$, where $SS_{tot} = \sum_i (y_i - \bar{y})^2$ is the total sum of squares and $SS_{err} = \sum_i (y_i - f_i)^2$ is the residual sum of squares. In the above, $\bar{y}$ is the mean which can be illustrated by $\bar{y} = \frac{1}{n}\sum_i^n y_i$, and f_i is an associated modeled value. R^2 exists between zero and one. The higher the R^2 is, the better the polynomial fits. This conclusion is more appropriate for linear system. If it tends to be nonlinear system, the judgement can be simply expressed as $SSE = \sum_i (y_i - f_i)^2$. The conclusion is in the opposite way that the lower SSE is, the better the polynomial fits.

Since level 10 is chosen in experiment, in order to get a more precise equation between power and angular velocity, a great many trials for calibration of level 10 are arranged. On the one hand, linear relationship is perfectly confirmed; on the other hand, the effort is made to control the power output at a relative low value to examine if the line cross the zero points. Theoretically, the curve is supposed to pass through zero of power output and zero of angular velocity. But in cranking activity, it is really difficult to keep angular velocity constantly at specific low power, which makes the curve not pass zero. While referring high angular speed, it needs quite strong force to maintain the speed continuous, which results in only limited trials are performed in high speed. The following figure (Figure 6.7) is the precise calibration of level 10.

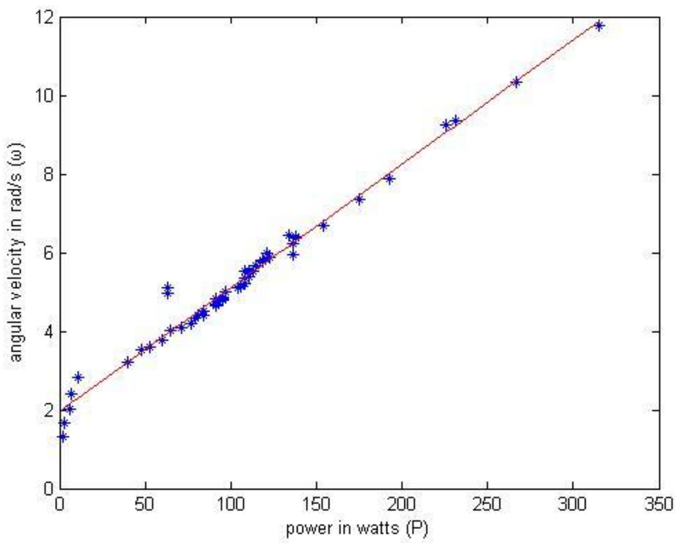

Figure 6.7: Calibration of Level 10.

The relationship between angular velocity and power is expressed as P=31.85ω-62.60. The characteristic values are 4.13, 195.85 and 0.98 of SS_{err}, SS_{tot} and R^2 within 95 % confidence interval.

6.3 External work calculation

The way to calculate external work bases on the combination of detection of instantaneous angular velocity and the function of power with the only variable of Instantaneous angular velocity. After the instantaneous power for 8 s is plotted, the integration of the product of instantaneous power output and time for 5 s starting with the occurrence of peak power is obtained by $W = \int_{T(Pmax)}^{T(Pmax)+5} P\ dt$, where W means external work, P means power and T(Pmax) stands for when the occurrence of peak power is gained. The program is attached in Appendix C.

The way to calculate peak power is divided into two cases. One is that the occurrence of peak power is within the first three seconds. And then the peak power is easily gained by locating the maximum. The other one is that the occurrence of peak power appears later than three seconds. In this case, the occurrence is found either at the apex of velocity if it exists a small peak in the first three seconds or detected by the degree of inclination of instantaneous power suddenly turns from steep to gentle if the velocity is uninterruptedly increasing in the first three seconds.

In Figure 6.8, it plots power output, where the occurrence of peak power is marked with a red dot. The area filled with red slashes is the external work. In this example, the occurrence of peak power happens at Second 2, peak power is 170.45 W and external work is 738.56 J.

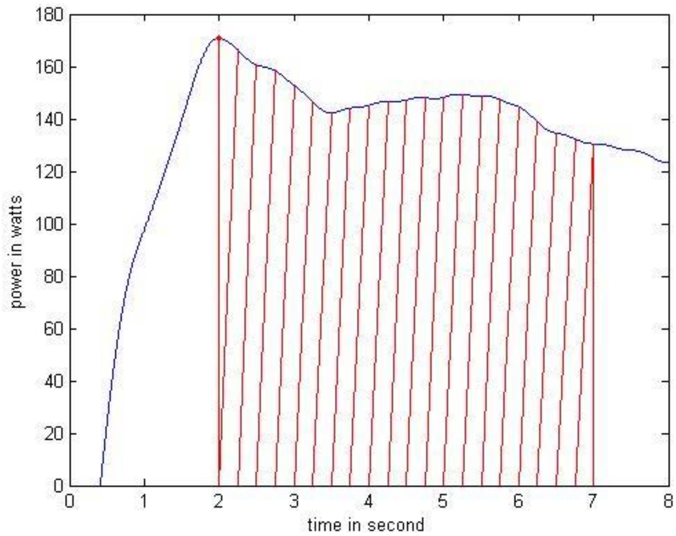

Figure 6.8: External work.

Chapter 7
Pilot experiment

The experiment protocol is tested to examine the feasibility of protocol. For instance, it mainly tests if two subjects can be handled at one time and the physical stress subjects feel from this intense activity in order to improve the formal experiment and ensure it works smoothly. There are 24 trials in total for one subject. The whole experiment lasts approximately 2.5 h. The equipment is adjusted to crank-axle height of 87, 92, 97, 102, 107 and 112 cm and crank arm length of 17.5, 20, 22.5 and 25 cm. The sampling frequency is set 10000 Hz. All the procedures run through on two male subjects.

7.1 Procedure

The pilot experiment generally includes six steps. It demonstrates all the details in the following paragraphs.

Step 1: Measure anthropometric characteristics containing weight, height and arm span of the subjects in millimeter accuracy. Explain to the subjects about Borg Scale (15 point scale, Appendix E). The crank-axle height tests are in a fixed order from the highest to the lowest. Randomize the trials of crank arm length tests under each height condition.
Step 2: Self warm up. Subjects perform standing forward grinding for 10 min at level 10 with moderate effort. The aim is to get familiar with grinding activity and prevent subjects from getting hurt in the following experiment.
Step 3: All the subjects complete an 8 s standing forward grinding with maximum effort at each combination of crank-axle height and crank arm length against the resistance of level 10. Each trial starts with left arm stays vertically upwards. Subjects have to maintain the whole feet stepping on the footplates during grinding.
Step 4: A verbal 3 s countdown is given to help subject focus on the coming trial.
Step 5: Rest interval is 5 min between trials.
Step 6: After each trial, ask the subject to score the degree of the trial according to Borg Scale.
Step 7: Two subjects take turns to complete the experiment.

7.2 Result

The result of the pilot is shown after the information of subjects. The unit of crank arm length (expressed as length in the table) and crank-axle height (expressed as height in the table) is centimeter. The testing order, the scale of each trial, the time of occurrence of peak power (s) and external work (KJ) according to each combination of crank arm length and crank-axle height are included and shown in the table encircled with bold frame which is presented as an example in the following small table.

Trial number	Borg scale
Occurrence of peak power (s)	External work (KJ)

Subject 1
Age: 24
Weight: 60.0 kg
Height: 177.8 cm
Arm span: 179.0 cm

Height \ Length	17.5		20		22.5		25	
112	2	12	1	14	3	13	4	14
	2.28	1.92	2.96	1.90	2.32	2.04	2.18	2.05
107	6	16	8	15	7	14	5	15
	2.52	1.96	2.30	1.93	2.36	1.94	2.06	2.07
102	11	16	9	15	10	14	12	14
	2.94	1.93	2.24	2.02	2.06	1.91	2.18	2.05
97	14	16	16	16	15	14	13	15
	2.42	1.98	2.48	2.02	2.10	1.99	2.24	2.04
92	18	16	19	15	20	13	17	16
	2.96	1.87	2.48	2.01	2.64	2.05	2.30	1.98
87	23	15	24	15	21	14	22	15
	2.58	1.94	2.28	1.89	2.18	2.04	2.18	2.03

Subject 2
Age: 26
Weight: 62.4 kg
Height: 169.0 cm
Arm span: 172.0 cm

Height \ Length	17.5		20		22.5		25	
112	3	15	2	15	4	15	1	13
	2.14	2.03	2.10	1.88	1.94	2.01	1.98	1.87
107	8	17	7	15	5	15	6	16
	2.24	1.91	2.56	2.05	2.64	2.05	2.52	2.00
102	9	18	10	15	12	14	11	13
	2.90	1.89	2.22	1.99	2.46	1.64	2.46	1.90
97	13	15	14	14	16	15	15	15
	2.38	1.84	2.80	1.86	2.20	1.93	2.28	1.68
92	17	17	19	12	18	12	20	13
	2.16	1.79	1.98	2.02	1.96	1.79	2.24	1.62

87	24	17	23	17	21	14	22	14
	2.46	1.85	2.28	1.99	2.24	1.82	2.28	1.92

7.3 Summary

According to the feedback from the subjects, during the test, it is reported that subjects feel no discomfort other than just a bit heat generating from the muscles around the shoulders and in the upper arms. Afterwards it takes them days to recover but hardly influences on normal activities.

From the data, no remarkable external work drop, the scale does not fluctuate sharply and some trials are scored high which could be on account of the unsuitable combination of height and length in terms of the subject's own physical condition.

In addition, whether the sampling frequency is enough is in doubt, since it is not good at detecting all the intact revolutions from Channel N during the experiment. Then an increase of sampling rate to 20000 Hz considered high enough to identify revolutions is applied in the formal experiment. Randomization of the trials should be done in a larger extent, which means the crank arm length and crank-axle height are totally and completely randomized except for randomizing only the crank arm length for the first two crank-axle heights which are barely adjusted within a short time.

Based on the above points, in the experiment, sampling frequency is increased to 20000 Hz and randomization is in a large extent. Except for these two points, the rest of experiment setup is kept the same as pilot experiment.

Chapter 8
Experiment

Based on the summary of the pilot, the improved protocol and related result of the experiment are shown in this chapter.

8.1 Experiment protocol

Eight male with stature between 170 and 190 cm are recruited in the experiment. They are required to wear gym shoes and sport suits and not to do strenuous exercise one day before experiment. The crank-axle height range is 87, 92, 97, 102, 107 and 112 cm (standard 87 cm) and the crank arm length range is 17.5, 20, 22.5 and 25 cm (standard 25 cm). All the footplates used to adjust the crank-axle height are wrapped with the same skidproof material to get rid of slide and maintain similar friction. The sampling frequency is ascended to 20000 Hz. The experiment is viable for two subjects testing together. Besides, compared to changeable crank arm lengths based on the fixed crank-axle height, randomization of the trials is in a wide extent.

Experiment steps:

1. Measure anthropometric characteristics (height, weight and arm span) of the subjects in millimeter accuracy. Tell the subjects about Borg Scale (15 point scale).
2. Self warm up. Subjects perform standing forward grinding for 10 min at level 10 but with moderate effort. The aim is to get familiar with grinding activity and prevent subjects from getting hurt in the following experiment.
3. All the subjects complete an eight seconds maximum effort standing forward grinding at each combination of crank-axle height and crank arm length against the resistance of level 10, which means 24 trials in total for each subject. Each trial starts with left arm stays vertically upwards. Subjects have to maintain the whole feet stepping on the footplates during grinding.
4. A verbal three seconds countdown is given to help subject focus on the coming trial.
5. Rest interval is 5 min between trials, the experiment lasts about 2.5 h.
6. After each trial, ask the subject to score the degree of the trial according to Borg Scale.
7. First 4 trials are under the crank-axle height of 112 cm, the testing crank arm length is randomized.
8. Trial 5 to 8 are under the crank-axle height of 107 cm. In order to have an enough time to adjust the height, the crank arm length tested of trial 5 is the same as that of trial 4. The crank arm length of the rest of 3 trials is randomized.
9. Trial 9 has the same crank arm length as trial 8 based on the crank-axle height of 102 cm.
10. From trial 10 to 24, it is totally randomized on both crank-axle height and crank arm length.

Timetable for the experiment:

Subject 1		Subject 2	
Trial	Trial duration	Trial	Trial duration
1	00:00:00--00:00:08	1	00:02:30--00:02:38

2	00:05:08--00:05:16	2	00:07:38--00:07:46
3	00:10:16--00:10:24	3	00:12:46--00:12:54
4	00:15:24--00:15:32	4	00:17:54--00:18:02
5	00:20:32--00:20:40	5	00:23:02--00:23:10
6	00:25:40--00:25:48	6	00:28:10--00:28:18
7	00:30:48--00:30:56	7	00:33:18--00:33:26
8	00:35:56--00:36:04	8	00:38:26--00:38:34
9	00:41:04--00:41:12	9	00:43:34--00:43:42
10	00:46:12--00:46:20	10	00:48:42--00:48:50
11	00:51:20--00:51:28	11	00:53:50--00:53:58
12	00:56:28--00:56:36	12	00:58:58--00:59:06
13	01:01:36--01:01:44	13	01:04:06--01:04:14
14	01:06:44--01:06:52	14	01:09:14--01:09:22
15	01:11:52--01:12:00	15	01:14:22--01:14:30
16	01:17:00--01:17:08	16	01:19:30--01:19:38
17	01:22:08--01:22:16	17	01:24:38--01:24:46
18	01:27:16--01:27:24	18	01:29:46--01:29:54
19	01:32:24--01:32:32	19	01:34:54--01:35:02
20	01:37:32--01:37:40	20	01:40:02--01:40:10
21	01:42:40--01:42:48	21	01:45:10--01:45:18
22	01:47:48--01:47:56	22	01:50:18--01:50:26
23	01:52:56--01:53:04	23	01:55:26--01:55:34
24	01:58:04--01:58:12	24	02:00:34--02:00:42

8.2 Experiment result

The data of all the subjects is attached in Appendix F. Subjects have no problem in continuous grinding with maximum effort for 8 s. The estimation about level of effort from subjects is almost the same as those in pilot. Heat production from muscles around shoulders and in upper arms is the main feeling about this intense activity. One subject reports low back pain after the whole experiment gets finished. Besides, one subject has a wide gap between stature and arm span.

The processed relationship between instantaneous power output and time ought to ideally like the graph below (Figure 8.1), where the occurrence of peak power is marked by a red dot. In general, the occurrence of peak power appears around Second 2 and the power output drops, the extent of drop mostly depends on how well the power is retained. However, there is another case that it produces relatively constant power which implies power is well maintained during the trial (Figure 8.2). Moreover, in some trials, the peak power starts near the third second (Figure 8.3) which means the high power output from this subject is not as good as the other subjects who have peak power come early.

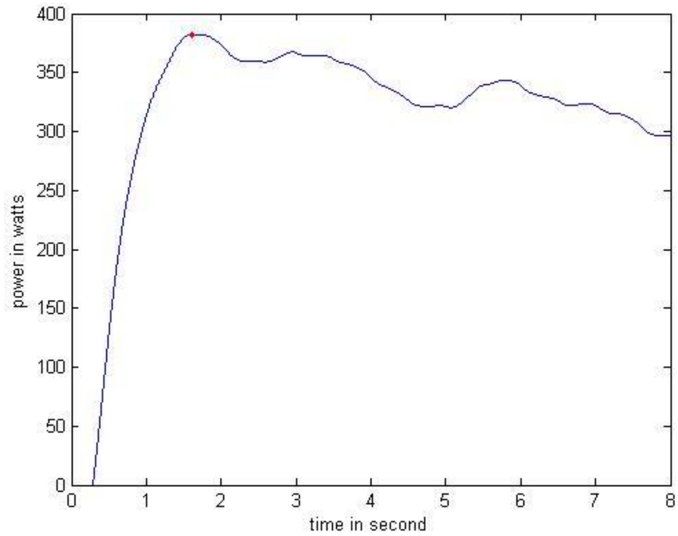

Figure 8.1: Instant power output.

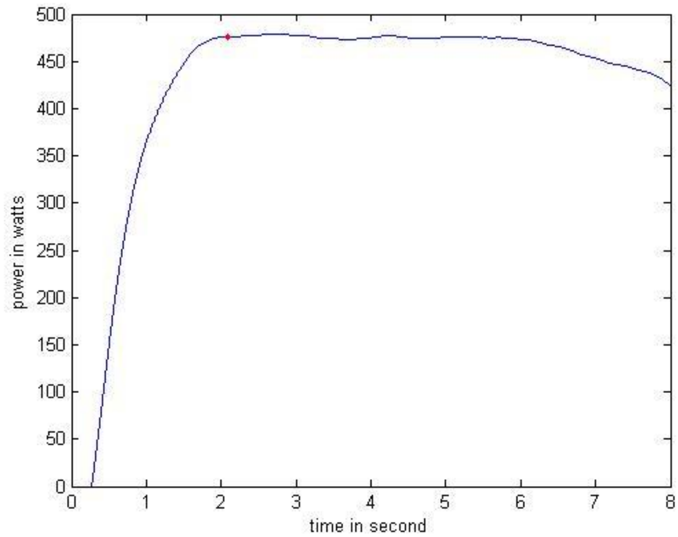

Figure 8.2: Relatively constant power output.

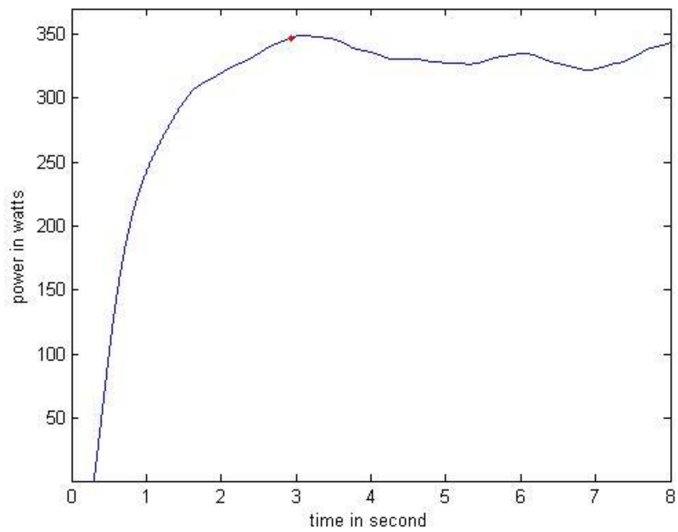

Figure 8.3: Occurrence of peak power appears later than Second 2.

As the following figure (Figure 8.4) shows, the location of peak power is in the middle of trial duration instead of the first three seconds, but clearly there is a small peak happens around Second 2. In this situation, the first small peak could result from grinding in the nearest approximation of maximum effort, it is hard for the subject to tell the difference when the trial is in process. In contrast, from Figure 8.5, it also has the peak power later than three seconds with power output sustaining growing. The method to determine the occurrence of peak power is replaced with detection of the degree of inclination that turns from steep to gentle.

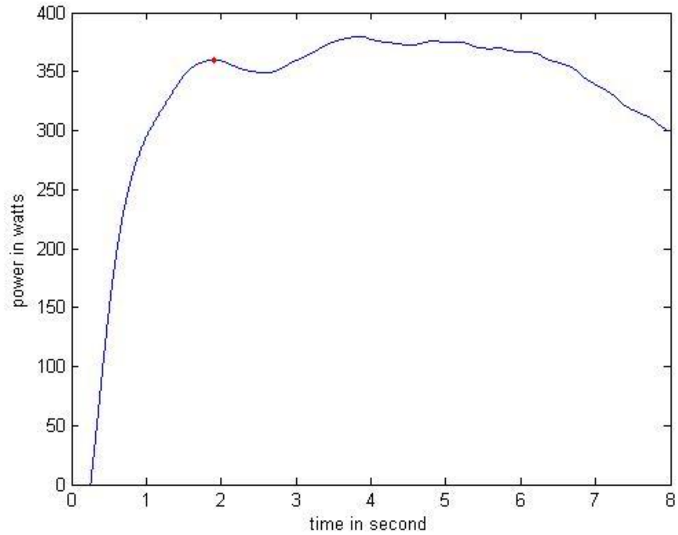

Figure 8.4: Occurrence of peak power is later than the third second.

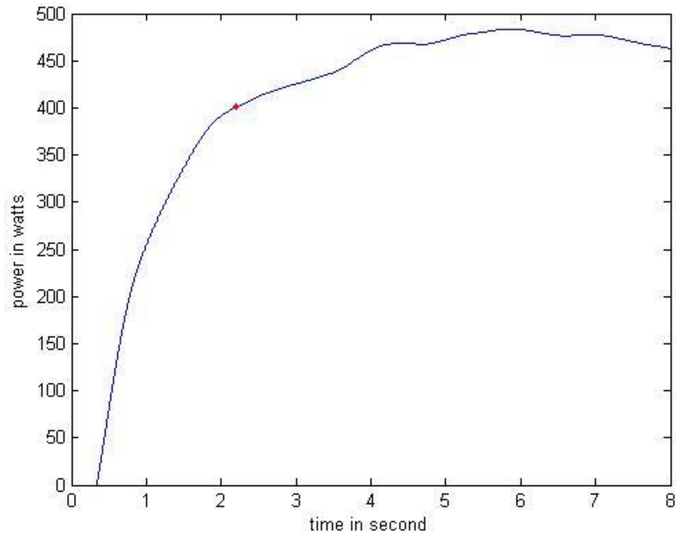

Figure 8.5: Occurrence of peak power is later than the third second with power increasing.

Most subjects perform in a relatively constant power output with a trend of power drop at some point. Since some trials have the occurrence of peak power happen after the third second, which means grinding for only eight seconds might be too short to calculate external work for five seconds beginning with the occurrence of peak power. The method to solve this problem is to locate the time when the slope of power output curve suddenly changes from high to low during the first three seconds. However, in order to stick to the definition of external work for five seconds, prolong the duration of trials could provide sufficient time for external work calculation. Since the subjects are not professionals, extending trial duration could induce fatigue so easily that it might make a challenge to all the subjects.

Nevertheless, there are some trials with sharp jump down in power output in the curves (Figure 8.6), which is deemed as failure of trials and excluded from the analysis of optimum combination of crank arm length and crank-axle height afterwards. Two trials (Trial 6 from Subject 3 and Trial 22 from Subject 8) are eliminated based on this reason. One trial from another subject (Trial 6 from Subject 6) is also excluded on account of an extremely high result of external work compared to the rest of trials. The reason could be a different cranking technique is applied in that trial or hardware problem.

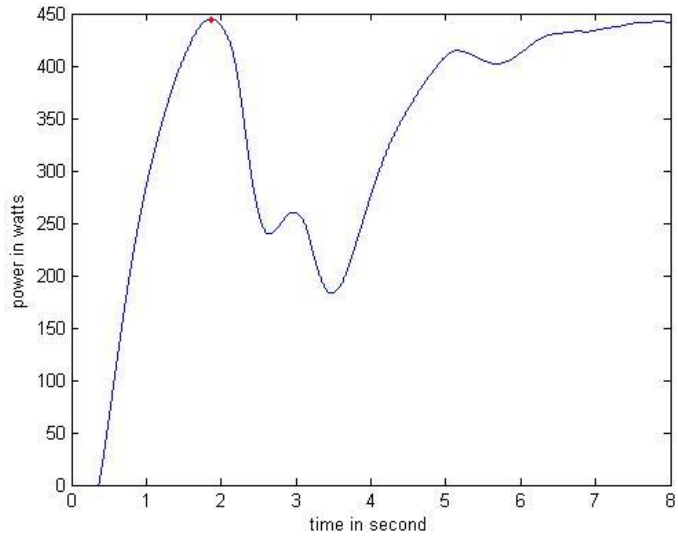

Figure 8.6: An example of a failed trial.

8.2.1 Optimum crank arm length based on a fixed crank-axle height

Due to the conclusions from a previous study [4], it has been suggested that 12-12.5 % of arm span and 50-60 % of stature are respectively optimum crank arm length and crank-axle height. Parabola curves were observed for peak power with crank arm length and crank-axle height. In order to examine the optimum crank arm length based on a fixed crank-axle height of 87 cm used in the race at present, 2D plots are needed. Due to the conclusion from a previous study [4], it showed second degree polynomial fit of peak power with crank arm length and crank-axle height, which may be used for reference in analysis of optimum crank arm length and crank-axle height in this study.

Figure 8.7 shows quadratic polynomial fit for the first four subjects. The first, third and fourth subjects separately plot downward curves. The valley happens at about 13 % of arm span. The external work increases as the percentage of arm span decreases from 13 %. In contrast, the second subject has an upward curve, where the peak is around 11 % of arm span. In general, the optimum crank arm span locates at 9-11 % of arm span only based on this graph.

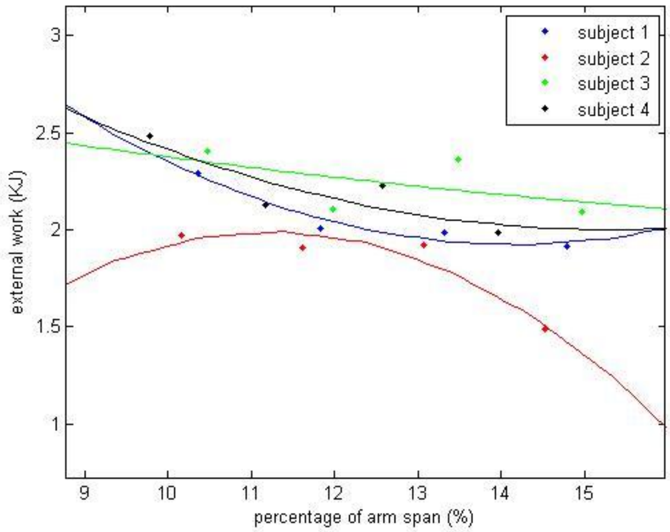

Figure 8.7: Relationship between external work and percentage of arm span for the first four subjects.

It illustrates the relationship between external work and percentage of arm span for the last four subjects in Figure 8.8. The highest external work appears around 8.5-11 % of arm span for the last three subjects but for Subject 5, the value at 11% of arm span almost hits the bottom. The optimum crank arm length could be better when it is smaller than 9 % of arm span.

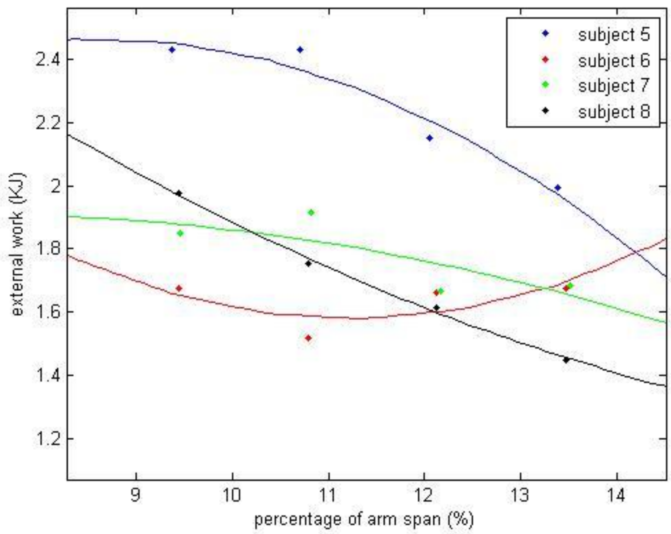

Figure 8.8: Relationship between external work and percentage of arm span for the last four subjects.

8.2.2 Optimum crank-axle height based on a fixed crank arm length

The optimum crank-axle height is tested in the condition of crank arm length of 25 cm. In Figure 8.9 containing curves for the first four subjects, only the third subject shows a different shape of curve. The rest of subjects produce upward curves and the great external work is generated at

60-68 % of stature for subject 2 and 4 and 50-60 % of stature for the first subject. Albeit the best interval for the third subject could be either lower than 50 % or higher than 62% of stature. It is hardly to tell the specific optimum range from this graph.

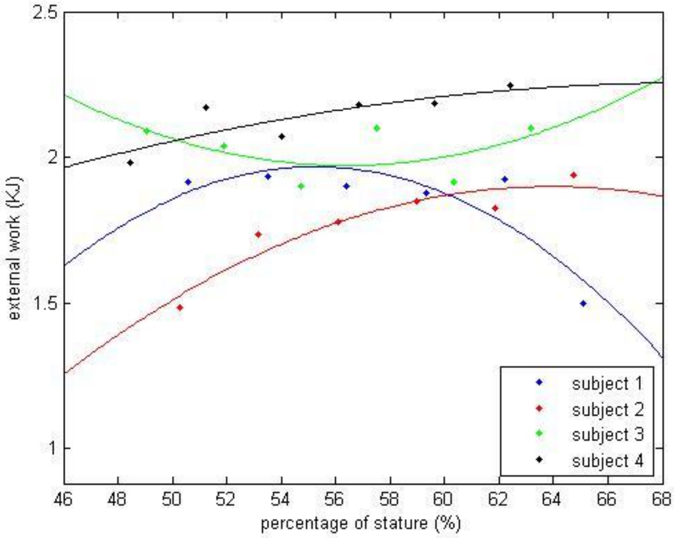

Figure 8.9: Relationship between external work and percentage of stature for the first four subjects.

The parabolas for the last four subjects are shown in Figure 8.10. All these four subjects exhibit upward curves, where it is easy to tell the range of 50-56 % of stature assists to generate a large amount of external work.

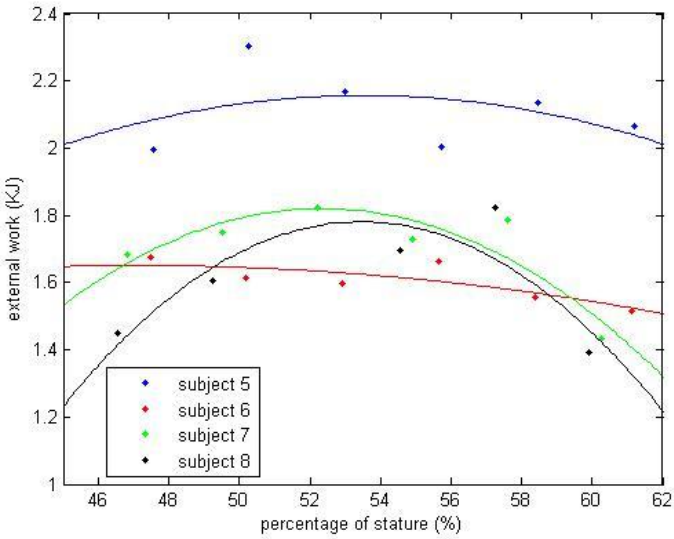

Figure 8.10: Relationship between external work and percentage of stature for the last four subjects.

In conclusion, the optimum crank arm length is probable 9-11 % of arm span and the optimum crank-axle height is 60-68 % or 50-56 % of stature. Apparently, the goodness of fit seems not good enough, plus especially for optimum crank arm length test, it also makes sense to reckon it linear. Therefore the optimum crank arm length and crank-axle height ought to be investigated in another way under combining with the rest of trials from all the subjects for example through polynomial 3D plotting.

8.2.3 Optimum combination of crank arm length and crank-axle height

Based on the 24 trials for each subject, a 3D polynomial fit with degree 3 for crank arm length and degree 5 for crank-axle height is applied to get a high fitting result. The data is individually normalized by dividing by the maximum value of external work.

For the first subject, the best trial happens to the combination of crank arm length of 17.5 cm and crank-axle height of 107 cm, which are separately 10.36 % of arm span and 62.21 % of stature. The value R^2 to estimate the goodness of polynomial fit is 0.98 within 95 % of confidence bound. From the polynomial fit (Figure 8.11), above 95 % of maximum external work, the area is 10.3-10.7 % of arm span with 57-64 % of stature. When the standard extends to higher than 90 % of maximum external work, the region becomes to two sub-regions; one is 10.3-11 % of arm span with 56-64.5 % of stature and the other one is 12.5-14 % of arm span with 55-58 % of stature. From the shape of the darkest zone of the right graph, there is expected to be a dark region when the crank arm length changes from 10.3 % of arm span to a lower value about 10 %. In general, it could be predicted that the optimum percentage is 10-11 % of arm span with 56-64.5 % of stature.

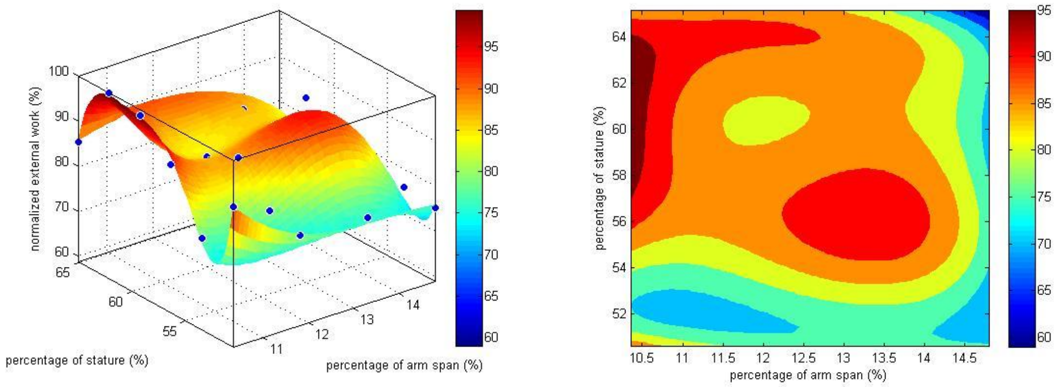

Figure 8.11: Polynomial fit for Subject 1.

For the second subject, the max external work appears at the combination of crank arm length of 17.5 cm and crank-axle height of 92 cm, which are separately 10.16 % of arm span and 53.43 % of stature. The goodness of fit is 0.95. Figure 8.12 shows different areas with dark color: 10-13.5 % of arm span with 50-54 % of stature and 10-11 % of arm span together with 62-64 % of stature based on 95-100 % of maximum external work. The areas increase to 10-14 % of arm span with 50-56 % of stature and 10-12 % of arm span with 60-64.5 % of stature based on 90-100 % of maximum external work.

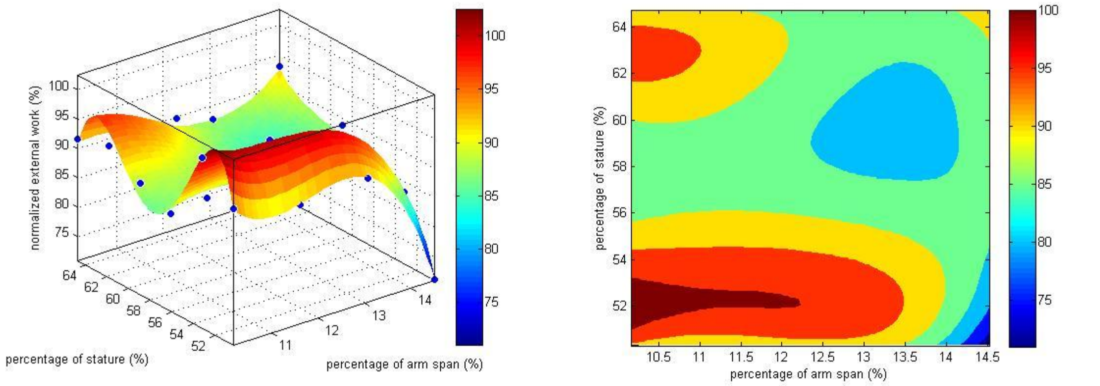

Figure 8.12: Polynomial fit for Subject 2.

For the third subject, after excluding the bad trial (Trial 6), the highest value is at the combination of crank arm length of 17.5 cm and crank-axle height of 112 cm, which account for 10.48 % of arm span and 63.17 % of stature. The fit level is 0.89. From the graph below (Figure 8.13), when the benchmark is 95 % of the maximum, 10.4-12 % of arm span with 58-63 % of stature is the best combination and grinding under 10.4-10.7 % of arm span with 49.5-52 % of stature produces acceptable external work. Based on the shape of the area with high external power output, it could be deemed that the optimal range is 10-12 % of arm span with 58-63 % of stature.

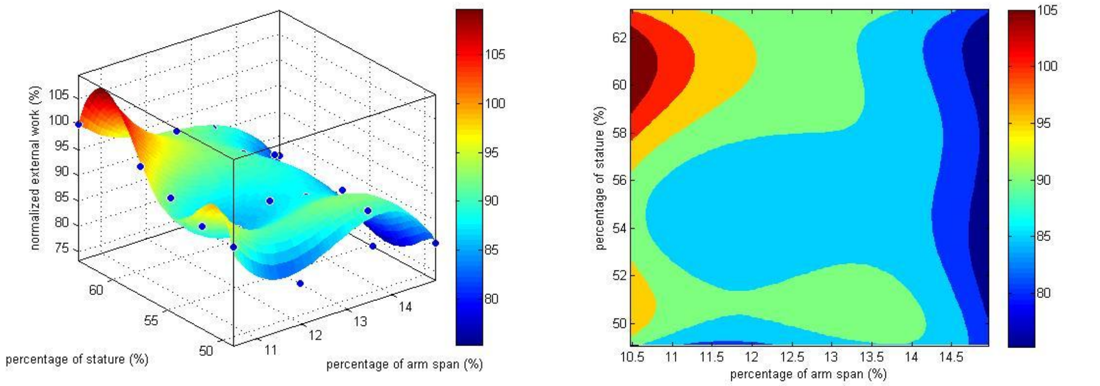

Figure 8.13: Polynomial fit for Subject 3.

For the fourth subject, the peak external work arises at crank arm length of 17.5 cm and crank-axle height of 112 cm, which is 9.78 % of arm span and 62.4 % of stature. The fit level is 0.93. Figure 8.14 shows that above 95 % of peak external work, the area is 9.7-10.5 % of arm span with 58-62.5 % of stature. However, above 90 % of peak external work, there is no obvious difference in the percentage of arm span less than 13.5 % while with the percentage of height between 60 % and 62.5 %. Similarly, in the extent of 9.7-10.5 % of arm span, no significant changes happen higher than 55 % of stature. Due to the shape of the darkest zone, it could predict the best value extends to 9.5-10.5 % of arm span with 58-63 % of stature.

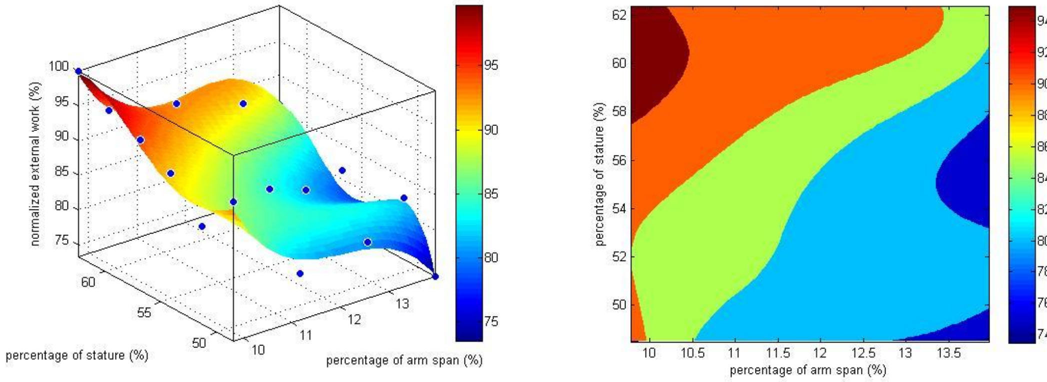

Figure 8.14: Polynomial fit for Subject 4.

For the fifth subject, the polynomial graph (Figure 8.15) shows that the greatest external work appears at the combination of crank arm length of 20 cm and crank-axle height of 112 cm, which occupy 10.71 % of arm span and 61.20 % of stature. It fits 94.93 % of the original tested external work. During the whole range of percentage of stature, the subject performs well when the crank arms are shorter than 11.5 % of arm span. At the same time, the best performance happens at 9.4-11.4 % of arm span with 55-62 % of stature. Besides, grinding at 9.4-10.6 % of arm span with 47.5-49 % of stature also performs well.

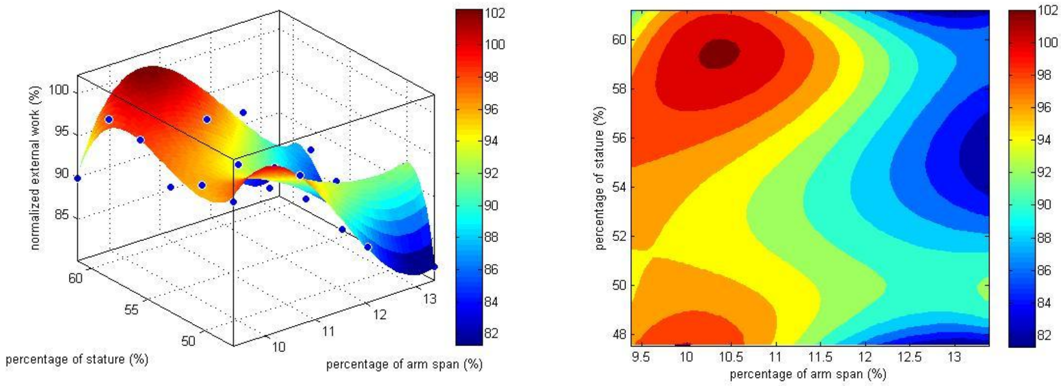

Figure 8.15: Polynomial fit for Subject 5.

For the sixth subject, excluding the failed trial, the highest external work is at the combination of crank arm length of 20 cm and crank-axle height of 112 cm, which mean 10.78 % of arm span and 61.1 % of stature. The degree of fit is 0.95. From polynomial fit (Figure 8.16), it shows one part at 9.5-11.25 % of arm span with about 61 % of stature, and the other part at the optimal interval is 9.6-11.4 % of arm span with 53.5-56.5 % of stature.

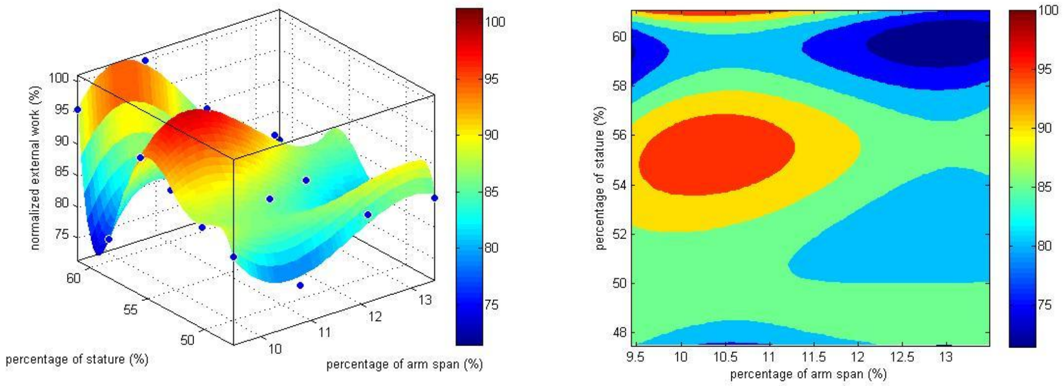

Figure 8.16: Polynomial fit for Subject 6.

For the seventh subject, the peak external work is at the combination of crank arm length of 17.5 cm and crank-axle height of 97 cm, which are respectively 9.46 % of arm span and 52.21 % of stature. The goodness of fit is 0.91. From polynomial fit (Figure 8.17), 9.4-9.7% and 11.7-12.7 % of arm span with 51-57.5 % of stature and 10-11.5 % of arm span with 57-59 % of stature are good combinations based on a higher percentage of maximum external work than 95 %. In the area of 9.4-13.3 % of arm span with 49-59 % of stature based on 90-100 % of maximal external work, it makes no remarkable difference in grinding performance while focusing on the figure.

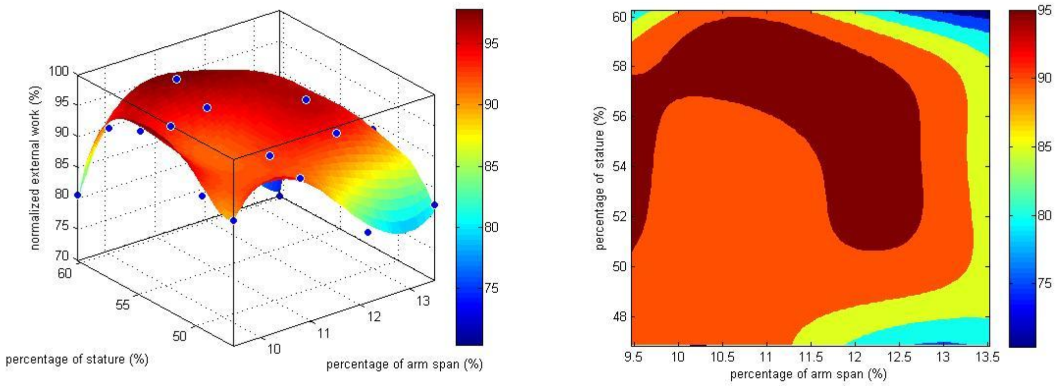

Figure 8.17: Polynomial fit for Subject 7.

For the last subject, the peak external work appears at the combination of crank arm length of 17.5 cm and crank-axle height of 102 cm, which account for 9.43 % of arm span and 54.57 % of stature. The degree of fit is close to 100 %. From the polynomial fit figure (Figure 8.18), above 95 % of maximum external work, the optimum area is 9.4-11 % of arm span with 51.5-56 % of stature. When the standard declines to 90 % of maximum external work, the region becomes two parts; one has approximately 9.4-11 % of arm span with 49-57 % of stature, the other one has about 9.4-10 % of arm span with 46-49 % of stature.

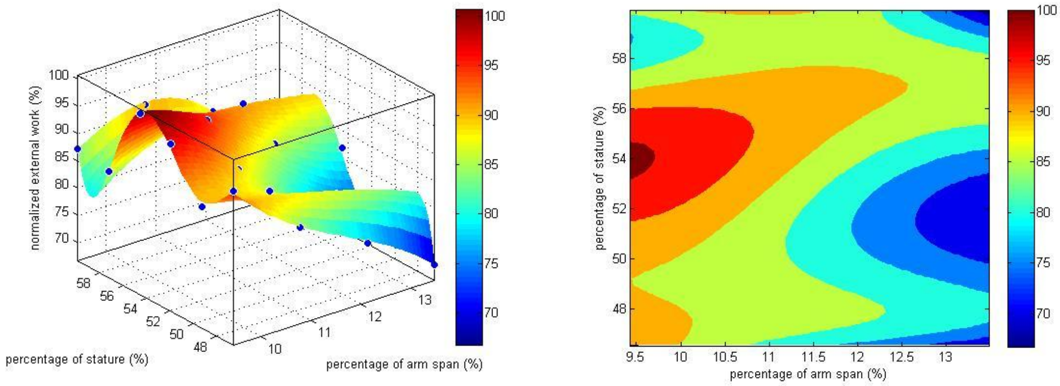

Figure 8.18: Polynomial fit for Subject 8.

In summary, one of the optimal ranges could be considered 10-11 % of arm span with 60-62 % of stature and the other one is 9.5-10.5 % of arm span with 52-54 % of stature. These ranges match the ones concluded from 2D plots based on the standard grinding pedestal setup.

In one special case, only the third subject shows a different anthropometric characteristic that the arm span is 10.3 cm shorter than height compared with the other subjects who have arm span almost the same as stature. This difference hardly has any significant influence on grinding performance or the optimum crank arm length and crank-axle height.

The following figure (Figure 8.19) demonstrates polynomial fit for all the individually normalized data. The goodness of fit is 0.47, not high enough. The optimal combination is 10-11 % of arm span with 59-64 % of stature. The relatively great normalized external work is mainly distributed throughout almost all the testing crank-axle length at short crank arm length. In comparison, the relatively small normalized external work spreads at long crank arm length, and the longer the crank arm length is, the smaller the normalized external work is produced.

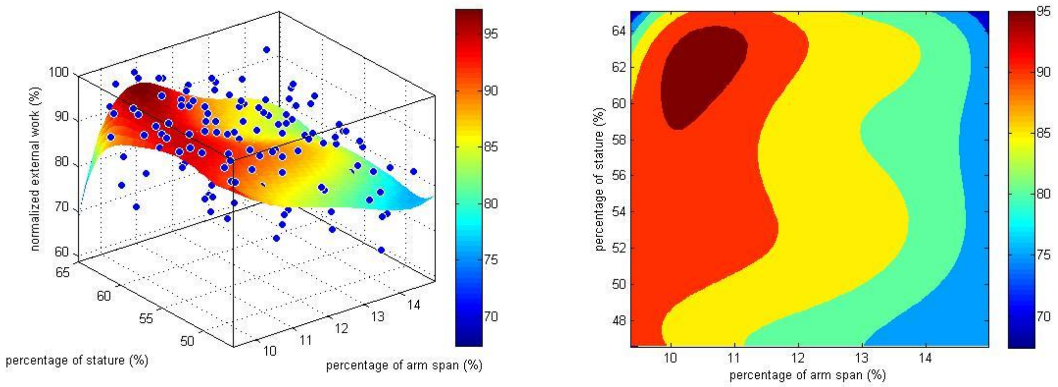

Figure 8.19: Polynomial fit for all the subjects.

Chapter 9

Synthesis

The following paragraphs firstly states the aspects needed to be improved in the experiment, and then compares the results of the experiment with some conclusions already exist from previous studies, afterwards the further work is described, and finally the optimal crank arm length and crank-axle height are concluded.

9.1 Discussion

In the experiment, there are some points needed to be modified and improved. It mainly focuses on three aspects: trial duration, grinding resistance and testing ranges of crank arm length and crank-axle height.

Firstly, since some trials have the peak power happen later than three seconds, in order to stick to the definition of external work for five seconds, prolongation of the duration of trials could provide sufficient time for external work calculation. However, due to the subjects are not professionals, extending trial duration could induce fatigue so easily that it might make a challenge to all the subjects.

Secondly, the ideally individual resistance is supposed to be used instead of unified resistance, which could elicit individual grinding performance at almost the same level to some extent. A previous research [24] records that the peak grinding velocity reached 120-150 rpm in America's Cup, which might be applied to set individual resistance via adjusting resistance until the subject achieves the grinding velocity of 120-150 rpm in a certain time.

Furthermore, the variation of crank arm length and crank-axle height should be extended particularly adding crank arm length shorter than 17.5 cm and crank-axle height higher than 112 cm to the testing ranges. The optimum crank arm length and crank-axle height would be more credible in the condition of wide testing ranges.

Finally, as for the limitation of structure of the grinding machine used in the experiment, during the test, there must have one person take the seat to put weight on the machine for keeping the machine stable. Since feet place between the hub and seat, it means that the distance between the hub and feet is fixed. It is possible for the tall subject to grind with a posture of benter back than the short subject. This fixed distance might have an influence on the cranking performance.

In terms of the result of the experiment, the combinations of 10-11 % of arm span with 60-62 % and 9.5-10.5 % of arm span with 52-54 % of stature generate great grinding performance. Since 60-62 % of stature is not included in the testing range from the existing figures for the last two subjects, it is unclear if the percentage fits for those subjects. Whereas compared to the standard crank arm length of 25 cm and crank-axle height of 87 cm, which approximately occupy 13.3 % of arm span and 46.28 % of stature for professional grinders in an average stature of 188 cm.

According to this experiment, crank-axle height of 46.28 % of stature is not tested in the experiment due to potential injury to low back [3-5], whether 46.28 % of stature is the best crank-axle height is still in debate. Based on the result of experiment, almost no subject performs very well under crank arm length of 13.3 % of arm span but it is still used in America's Cup. Difference in performances could result from the distance between handles of 48 cm in the race instead of 36 cm used in experiment, wind direction, deck heel and changeable resistance produced in the race.

From the result obtained, it is observed that grinding performance is more sensitive to crank arm length than crank-axle height. The external work fluctuates remarkably along with variation of crank arm length but slightly with variation of crank-axle height. Subjects perform better in the case of short crank arms than long crank arms. Changing crank arm length may be more efficient on improving grinding performance, especially adjusting it to about 10 % of arm span.

Power maintenance is equally important as the detection of peak power in grinding. The conclusion that the optimal crank arm length and crank-axle height are respectively 12-12.5 % of arm span and 50-60 % of stature based on analyzing peak power only concerning the time and amplitude of maximum power [4], which is different from the result of the optimal crank length of 10-11 % or 9.5-10.5 % of arm span and crank-axle height of 60-62 % of stature but similar with 52-54 % of stature concluded from this experiment which estimates performance depending on both occurrence of peak power and maintenance of power output. It is quite probable for power output to fall at some point after the occurrence of peak power. This power drop might be one of the major reasons to result in different optimum combinations between analyzing peak power and external work.

In the 32nd America's Cup, it comprised 20 ± 10 tacks and 8 ± 3 gybes in average, each tack took 5.5 ± 0.5 s and each gybe lasted 11.2 ± 1.4 s [1]. The time that peak power creates could be more important for tacking rather than gybing. Power might not significantly decrease during tacking only for 5 s. In comparison, since gybing takes twice time as tacking, the duration that power can be maintained should be definitely taken into consideration. Besides, the occurrence of peak power and maintenance of power could be easily affected by resistance. Grinding against a low resistance, peak power appears early and power output is easily retained consistently. The occurrence of peak power and power maintenance are contrary while grinding against a high resistance. No matter what resistance cranking is against, both in tacking and gybing, it would be great to produce peak power as fast as possible and as well maintain power the longer the better.

While with respect to rest interval, the exercise to rest ratio of continuing exercise for 8 s to 5 min rest in the experiment is much smaller than 1:6-1:3 in the race [1]. If the experiment is designed under the condition of 1:6-1:3 exercise to rest ratio, the results could be completely dissimilar which results from fatigue and it leads bias especially to the trials in high orders.

In the further study, in order to obtain a more valid result, first of all, a wider testing range especially for crank arm length less than 10 % of arm span and crank-axle height higher than 60 % of stature is required; secondly, a large number of subjects are needed; afterwards, a group of professionals is better to be recruited; finally, testing resistance might be increased to approximation of the load in the race. It is documented that in America's Cup, peak velocity is between 120 and 150 rpm [24] which can be used to investigate individually proximal resistance taken in the race.

In addition, two grinders work together at one winch, which means forward and backward grinding are performed at the same time in the race [10]. The optimum crank arm length and crank-axle height tested in this experiment is thought only working on forward grinding. The optimum crank arm length and crank-axle height used in backward grinding might be totally and completely different from forward grinding. The premise on paired grinding is that the optimum range for backward grinding has to be investigated. According to the optimum ranges for forward and backward grinding, two grinders whose arm spans and statures match the feature of grinding pedestal have to be arranged to collaborate.

9.2 Conclusion

The goal for this project is to examine the optimal crank arm length and crank-axle height with analyzing external work for 5 s based on standing forward grinding. Deck heel and changeable resistance are excluded in experimental environment. From the result of experiment, 9.5-10.5 % of arm span with 52-54 % of stature works on the second and last subjects but 10-11 % of arm span with 60-62 % of stature is the optimum range for the rest of subjects except the seventh subject and the performance of the second subject based on this range is acceptable. Plus, the last subject shows that high external work possibly happens when the crank-axle height is higher than 60 % of stature. Only for the seventh subject, grinding performance does not show prominent discrepancy under the combination of 9.4-13.3 % of arm span and 50-59 % of stature, which may derive from applying a different grinding technique. Overall, it could be concluded that the generally optimum combination producing great external work is 10-10.5 % of arm span with 60-62 % of stature.

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Appendix A

SolidWorks sketch

The SolidWorks CAD software is a 3-D modeling tool which applies mechanical design in order to enable designers sketch out ideas efficiently and quickly, experiment with features and dimensions, produce models and make particular drawings.

An intact handle includes the listing parts: the steel spindle (Figure A.1) with the diameter of 16mm, the interior iron handle (Figure A.2) with the shape of hollow circular cylinder which has inside diameter of 1.76 cm and outside diameter of 3 cm; the exterior handle (Figure A.3) made of rubber as a coating wrapping interior with the shape of hollow circular cylinder as well bearing inside diameter of 30mm and outside diameter of 35mm (in real, skidproof tape is instead of the coating), two T-shaped gaskets (Figure A.4) with inside diameter of 1.608 cm, middle diameter of 1.838 cm, outside diameter of 2.334 cm, thickness of 0.11 cm and total length of 1.252 cm and two gaskets (Figure A.5) with inside diameter of 1.595 cm, outside diameter of 2.564 cm and thickness of 0.15 cm.

Figure A.1: Steel spindle

Figure A.2: Interior metal handle.

Figure A.3: Exterior rubber handle.

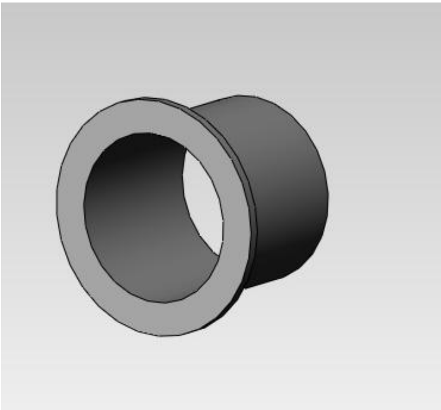

Figure A.4: T-shaped gasket.

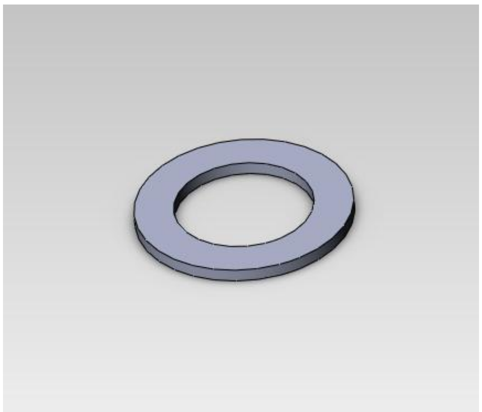

Figure A.5: Gasket.

The crank arm should be shaped as exactly same as the original one except for the grooves whose distances from the center to the handle's center are 17.5, 20, 22.5 and 25 cm respectively. The crank arm is made of aluminum with an M12 screw hole in. (Figure A.6).

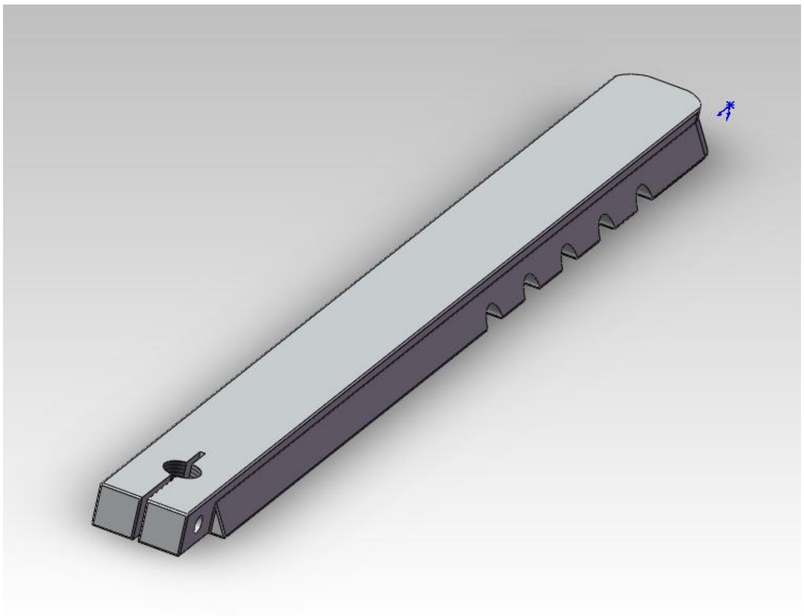

Figure A.6: Crank arm

To achieve the rotatable function, firstly, assemble T-shaped gaskets which are used to reduce attrition between interior handle and spindle to both ends of the interior (Figure A.7); secondly, fit interior and exterior handles together (Figure A.8), but in real, the exterior handle is replaced with one plastic handle; thirdly, screw the spindle to the crank arm, put one gasket through the whole spindle to reduce resistance between the handle and crank arm (Figure A.9) and finally, assemble the handle and the rest of parts, the other gasket is attached next to the T-shaped gasket near the top of the spindle, besides, to prevent the handle from sliding or dropping, there is a small groove at the end of spindle (Figure A.10), which can be blocked by a U-shaped clamp (Figure A.11).

Figure A.7: Assemblage of T-shaped gaskets and interior.

Figure A.8: Assemblage of interior and exterior.

Figure A.9: Assemblage of handle and spindle.

Figure A.10: Assemblage of all parts (except for U-shaped gasket).

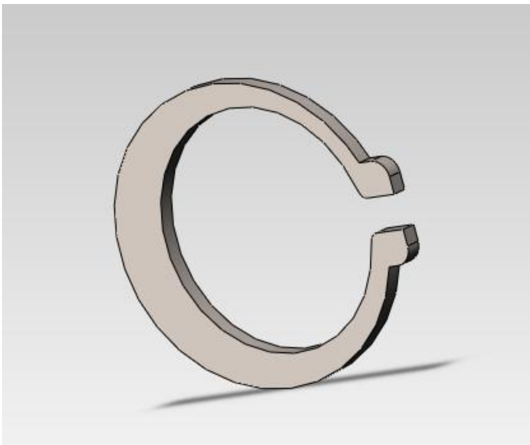

Figure A.11: U-shaped clamp.

The shapes of all the parts of handle and crank arm are shown before. The following four sketches (Figure A.12-A.15) respectively show the feature and information of the designs for the spindle of handle, the front, the back and the side of crank arm.

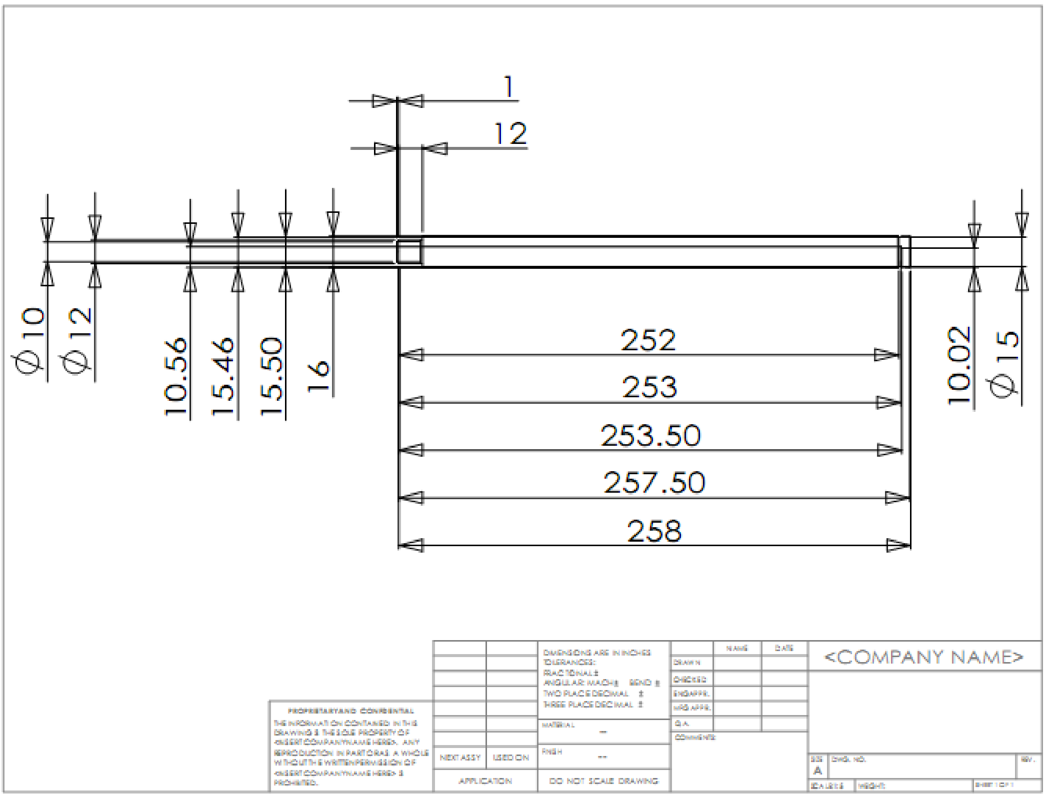

Figure A.12: Spindle of handle.

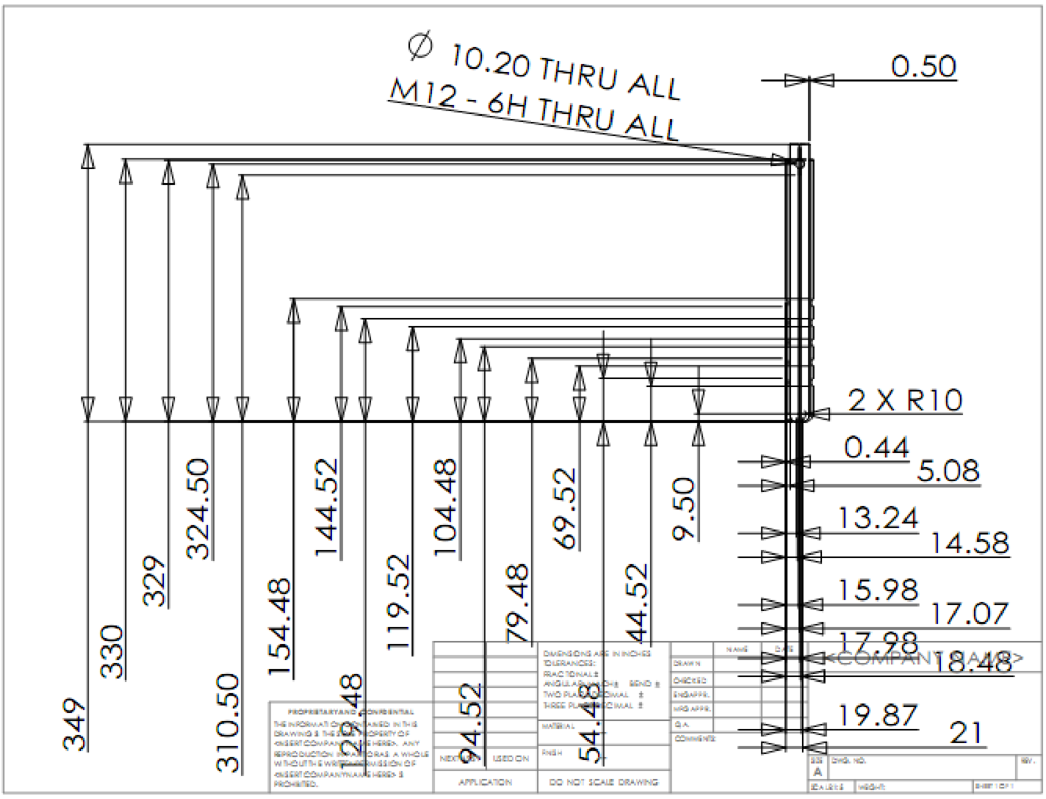

Figure A.13: The front side of crank arm.

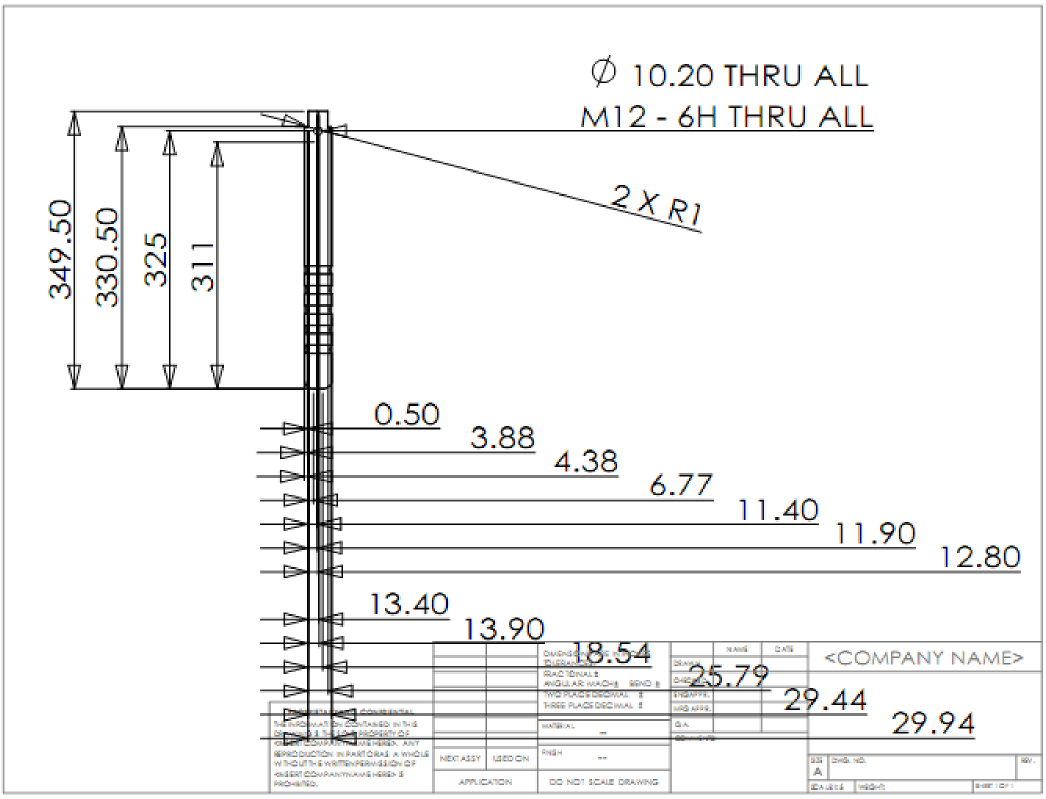

Figure A.14: The back side of crank arm.

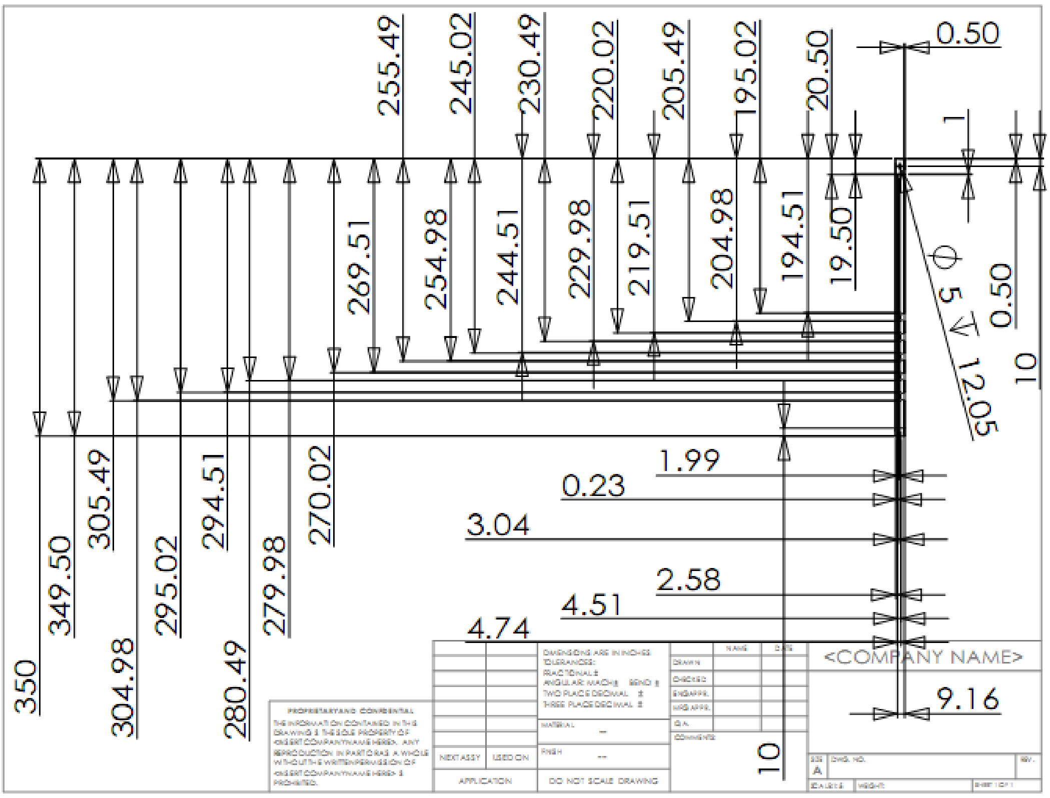

Figure A.15: The side of crank arm.

Appendix B

Matlab code for instantaneous angular velocity

```
close all
clear
load('file path');
```

Basic plots of channel N & A

```
Fs=20000;
sam=8*Fs; % the amount of samples
x=1:sam;
yN=dath001(1:sam,3); % channel N
yA=dath001(1:sam,1); % channel A
```

Revolutions indentification

```
for i=1:sam
    if yN(i,1)>0.5*max(yN);
        yNf(i)=yN(i,1);
    else
        yNf(i)=0;
    end
end
[pks,locs]=findpeaks(yNf); % find positions of boundaries of revolutions
r=length(locs); % intact revolution=r-1
startallrev=locs(1,1); % start of all revolution
endallrev=locs(1,r); % end of all revolutions
sampleallrev=endallrev-startallrev; % how many samples in all intact revolutions
```

The amount of peaks in all intact revolutions

```
for i=1:sam;
if i>=startallrev && i<=endallrev;
    yAallrev(i)=yA(i);
else
    yAallrev(i)=0;
end
end
yallrev=yAallrev'; % abstract all info of all the revolutions from channel A, keep the peak position
                        the same
yAallrev(yAallrev==0)=[]; % remove zeros since the info out of the revolutions is replaced with 0
                                to get a correct average
for i=1:sam;
if yallrev(i)>=mean(yAallrev); % make threshold
    ysquare(i)=1;
```

```
end
if yallrev(i)<mean(yAallrev);
        ysquare(i)=0;
end
end
yallsquare=ysquare'; % if value of channel A in all the revolutions is above threshold, input 1 in a
                                        array, otherwose input 0

amountpeak=0;
for j=2:sam;
if yallsquare(j)==1 && yallsquare(j-1)==0;
        amountpeak=amountpeak+1; % the amount of peaks in all intact revolutions in channel A
        loc(j)=j;
end
end
```

The amount of peaks in each revolution

```
for m=2:r
        peakonerev(1,m-1)=0;
for p=locs(m-1):locs(m)
        if yallsquare(p)==1 && yallsquare(p-1)==0;
        peakonerev(1,m-1)=peakonerev(1,m-1)+1;
        end
end
end
peaks=round(mean(peakonerev)); % peak amount in one intact revolution, which turns out to be
                                                    2048.
```

Instantaneous angular velocity

```
dis=2*pi/2048;

for i=1:sam;
if yA(i)>=mean(yA);
        yall(i)=1;
end
if yA(i)<mean(yA);
        yall(i)=0;
end
end
yAall=yall';

for j=2:sam;
        if yAall(j)==1 && yAall(j-1)==0;
                place(j)=j;
```

```
    end
end

peakloc=place';
peakloc(peakloc==0)=[]; % remove zero
peakloc(:,1)=peakloc(:,1)-1; % starts of peaks
peakdif=diff(peakloc); % the number of samples between peaks

si=length(peakloc);
for k=1:(si-1);
peakav(k)=dis*Fs/peakdif(k); % angular velocity in w/s
end
av=peakav';

rela(1:si,1)=(peakloc); % position where the peaks start
rela(2:si,2)=(av); % angular velocity
rela(2:si,3)=(peakdif); % time difference in samples

xi=rela(2,1):1:rela(si,1);
avall=interp1(rela(2:si,1),rela(2:si,2),xi,'spline','extrap'); % interpolation to make a continuous curve
avall(1:(rela(2,1)-1))=0;
avall((rela(si,1)+1):sam)=0;

figure()
[b,a]=butter(3,0.0001); % filter coefficients
angularfilt=filter(b,a,avall); % lowpass filter
plot(angularfilt);
set(gca,'XTickLabel',[0 1 2 3 4 5 6 7 8]);
axis([0 sam 0 max(angularfilt)+1]);
xlabel('time in second');
ylabel('angular velocity in rad/s');
```

Appendix C

Matlab code for external work calculation

Occurrence of peak power

```
[Bman,IXmax]=max(angularfilt);
if IXmax<=3*Fs % judge if peak power is in the first three seconds
    startpeak=IXmax;
    hold on
    plot(startpeak,angularfilt(startpeak),'r.')
end

if IXmax>3*Fs
der=diff(angularfilt(1:200:3*Fs))/(200/Fs); % slope
derchange=find(der<0); % find downward parts of the curve
change=length(derchange);

if change~=0; % if the curve goes up and down in the first three seconds
    for i=1:length(der)-1 % all the points that the curve turns
        if der(i)>0 && der(i+1)<0
            Bminder(i)=der(i);
            IXminder(i)=i;
            Bminder(Bminder==0)=[];
            IXminder(IXminder==0)=[];
        end
    end
    starts=(IXminder)*200;
    [BB,IXX]=max(angularfilt(starts));
    if BB-angularfilt(starts(1))>1; % compare the first turn with the turn with the highest value
        startpeak=starts(IXX);
    else
        startpeak=starts(1); % based on the apex
    end
    hold on
    plot(startpeak,angularfilt(startpeak),'r.');
end

if change==0; % if the curve only goes up in the first three seconds
    for l=1:length(der)-1 % find when the curve goes from sharp to gentle
        angle=atan(der)*180/pi;
        diffa=abs(diff(angle));
        [Bd,IXd]=max(diffa(75:length(diffa)));
        startpeak=(IXd+75-1)*200;
    end
```

```
    hold on
    plot(startpeak,angularfilt(startpeak),'r.')
end
end
```

External work

```
starttime=startpeak/Fs;
powerspot=(angularfilt-1.9656)/0.0314 ;% power at each sample
powerlow=find(powerspot<=0); % find samples where power is below zero
powerspot(powerlow)=0; % replace the power below zero with zero
figure()
plot(powerspot);
set(gca,'XTickLabel',[0 1 2 3 4 5 6 7 8]);
xlabel('time in second');
ylabel('power in watts');
hold on
plot(startpeak,powerspot(startpeak),'r.')
extwork=sum(powerspot(startpeak:(startpeak+5*Fs)))/Fs;
```

Appendix D
Grinding machine calibration

In the test, it is hard to keep a low power output constant in high levels because the system spends some time in increasing the resistance from zero to that is needed so that the subjects have to self-decide the start point that can be maintained constantly easily. In comparison, high power output is difficult to achieve in low level test, the stop line of power output is low in general. In order to obtain a relatively precise result, the power output is maintained in the range of 50 to 150 Watts. The calibration from level 1 to 9 and level 11 (Figure D.1 to D.10) is showed below with equations underneath, where P presents power output in watts and ω presents angular velocity in rad/s.

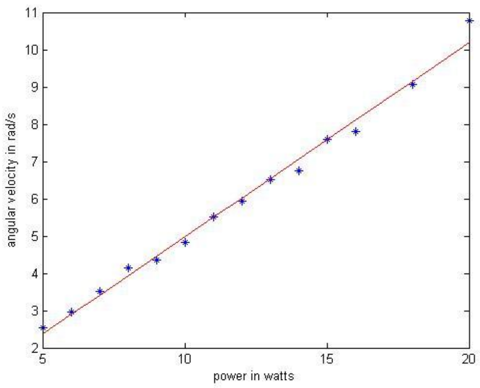

Figure D.1: Level 1, $\omega=0.52P-0.23$
$P=1.92\omega+0.44$

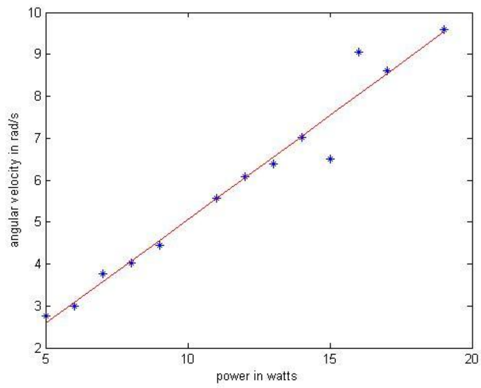

Figure D.2: Level 2, $\omega=0.50P+0.10$
$P=2.01\omega-0.20$

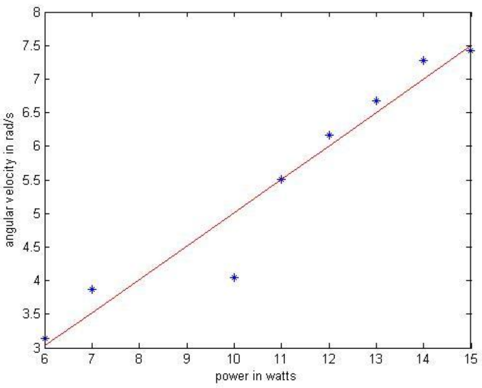

Figure D.3: Level3, $\omega=0.50P+0.04$
$P=2.01\omega-0.09$

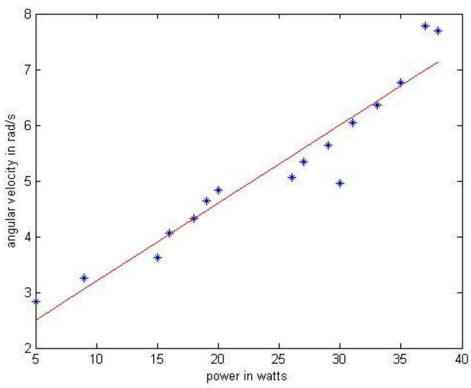

Figure D.4: Level 4, $\omega=0.14P+1.80$
$P=7.12\omega-12.79$

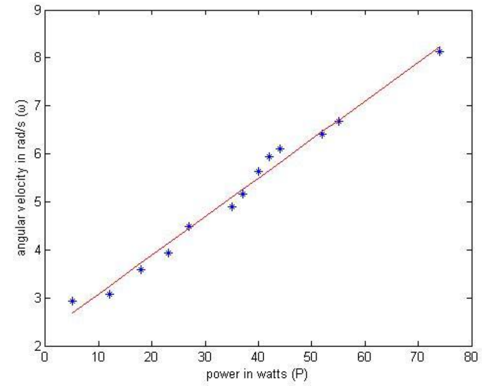

Figure D.5: Level 5, ω=0.08P+2.27
P=12.39ω-20.09

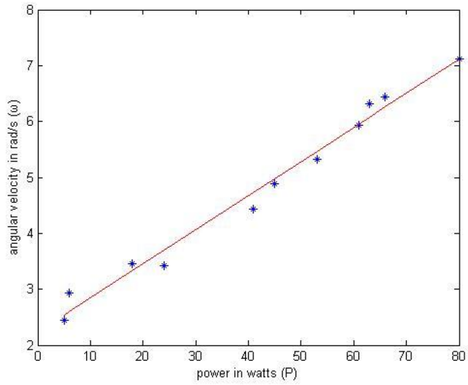

Figure D.6: Level 6, ω=0.06P+2.23
P=16.37ω-36.46

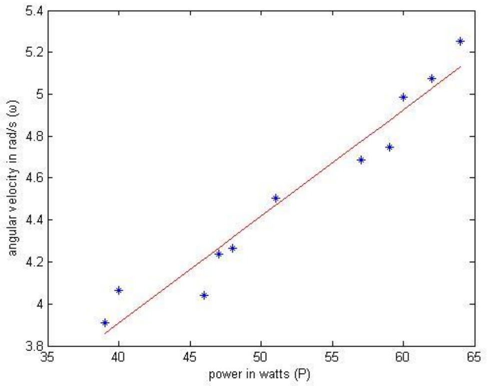

Figure D.7: Level 7, ω=0.05P+1.88
P=19.69ω-37.00

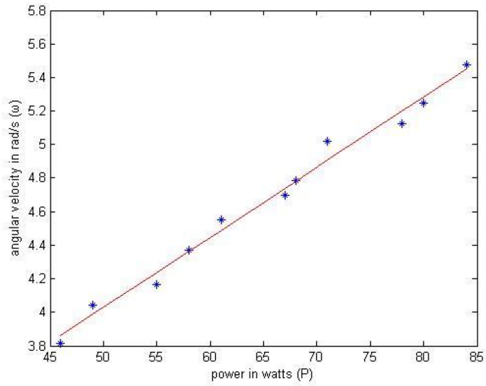

Figure D.8: Level 8, ω=0.04P+1.94
P=23.92ω-46.43

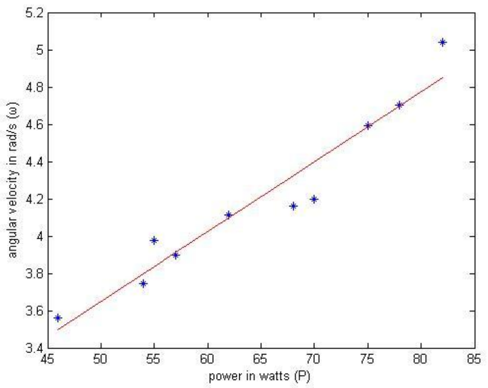

Figure D.9: Level 9, ω=0.04P+1.77
P=26.67ω-43.31

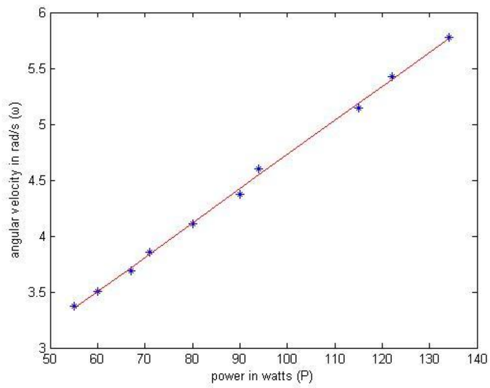

Figure D.10: Level 11, ω=0.03P+1.67
P=32.68ω-54.55

From the figures of level 1 to 9 and level 11, the overall relationship between power and angular velocity is linear. The range of R^2 is between 0.92 and 1.00. The smallest value appears from level 4, where the subject probably did not perform well in controlling cranking speed constant. The highest R^2 comes from level 11. The trend of the coefficient of P generally decreases while level increases. Ideally, the line should cross the point of zero in power output and zero in angular velocity; however, the system needs time to adjust resistance from level 0 to the level set up, plus in high levels constant cranking is hard to obtain at a low power output, it decreases accuracy of the result when zero points are added in plotting the relationship between power output and angular velocity due to a long interval between zero points and the rest of points obtained in the experiment. Apparently, the relationship between angular velocity and power of the levels tested is considered linear. It can be reasonably concluded that relationship between angular velocity and power output is linear for the whole levels of the machine.

Appendix E

Borg Scale

The Borg Scale is a simple method of rating perceived exertion (RPE) normally used in sports and particularly exercises testing, which is helpful to assess the intensity of training and competition. The original scale (Borg 6-20) measures exertion in a range between 6 and 20 where 6 is the lowest level and 20 is the highest. During the activity, a subject is required to honestly evaluate the level of effort and assign it a number between 6 and 20. In additional, 11 point scale (Borg CR10) is also a common method in use, where 0 is the lowest level and 11 is the highest.

There is also a correlation between RPE and general heart rate that Borg Scale is almost equal to heart rate divide by 10 for Borg 6-20. However, this calculation is only an approximation of heart rate, and the actual heart rate varies a bit depending on age, physical condition and medications. The Borg Scale is shown below.

Borg 6-20:

- 6 - 20% effort
- 7 - 30% effort - Very, very light (Rest)
- 8 - 40% effort
- 9 - 50% effort - Very light - gentle walking
- 10 - 55% effort
- 11 - 60% effort - Fairly light
- 12 - 65% effort
- 13 - 70% effort - Somewhat hard - steady pace
- 14 - 75% effort
- 15 - 80% effort - Hard
- 16 - 85% effort
- 17 - 90% effort - Very hard
- 18 - 95% effort
- 19 - 100% effort - Very, very hard
- 20 - Exhaustion

Borg CR10:

- 0 - Nothing at all
- 1 - Very light
- 2 - Fairly light
- 3 – Moderate
- 4 - Somewhat hard
- 5 – Hard
- 6
- 7 - Very hard
- 8
- 9

- 10 - Very, very hard

Appendix F

Experiment data

The unit of crank arm length (expressed as length in the table) and crank-axle height (expressed as length and height in the table) is centimeter. The result is shown and encircled by bold frame in the tables including the testing order, the score of each trial, the external work (KJ) and the time of occurrence of peak velocity (s) according to every combination of crank arm length and crank-axle height.

Trial number	Borg scale
Occurrence of peak power (s)	External work (KJ)

Subject 1
Age: 28
Weight: 71.1 kg
Height: 172.0 cm
Arm span: 169.0 cm

Length / Height	17.5		20		22.5		25	
112	4	15	2	12	3	13	1	11
	1.92	2.18	2.31	2.26	2.29	2.11	1.93	1.50
107	5	15	6	15	8	15	7	15
	2.05	2.56	2.19	2.20	2.30	2.21	2.19	1.93
102	13	15	23	18	9	15	22	17
	2.36	2.52	1.80	2.16	2.07	2.22	2.60	1.88
97	20	17	10	15	16	15	18	16
	2.11	2.34	2.95	2.26	1.96	2.47	2.35	1.90
92	12	16	21	17	15	16	24	18
	2.29	2.02	2.10	2.05	2.67	2.10	2.13	1.94
87	17	16	19	16	14	16	11	16
	2.20	2.30	2.62	2.01	1.71	1.99	2.26	1.91

Subject 2
Age: 30
Weight: 64.0 kg
Height: 173.0 cm
Arm span: 172.2 cm

Height \ Length	17.5		20		22.5		25	
112	4	13	1	10	3	11	2	10
	2.86	1.91	2.57	1.85	2.07	1.83	1.88	1.94
107	5	14	7	15	8	14	6	14
	2.10	1.95	2.33	1.97	2.35	1.77	2.40	1.82
102	17	16	11	15	9	14	19	16
	2.23	1.88	1.75	1.75	2.39	1.73	1.42	1.85
97	15	15	14	15	23	17	16	15
	1.91	1.83	2.05	1.90	1.90	1.86	2.16	1.78
92	22	17	18	16	24	17	13	15
	2.76	2.09	1.96	2.08	2.76	2.01	1.61	1.74
87	10	15	20	16	21	16	12	15
	2.97	1.97	2.59	1.91	1.88	1.92	1.51	1.49

Subject 3
Age: 25
Weight: 80.8 kg
Height: 177.3 cm
Arm span: 167.0 cm

Height \ Length	17.5		20		22.5		25	
112	2	8	3	8	4	8	1	8
	2.48	2.59	2.22	2.42	2.36	2.35	1.64	2.10
107	6	9	8	9	5	9	7	10
	1.87	1.72	2.57	2.53	2.04	2.31	1.50	1.92
102	20	9	9	9	24	4	15	9
	2.97	2.55	2.90	2.19	2.95	2.39	1.83	2.10
97	19	9	11	9	14	9	21	7
	2.98	2.48	2.96	2.20	2.44	2.26	1.65	1.90
92	16	9	12	9	13	8	22	6
	2.28	2.42	1.92	2.44	1.99	2.27	1.76	2.04
87	23	9	10	9	18	9	17	9
	2.51	2.40	1.94	2.11	2.09	2.37	2.80	2.09

Subject 4
Age: 25
Weight: 61.8 kg
Height: 179.5 cm

Arm span: 179.0 cm

Height \ Length	17.5		20		22.5		25	
112	3	12	4	12	1	11	2	11
	2.87	2.68	2.78	2.41	2.05	2.50	1.69	2.25
107	8	12	6	12	7	14	5	12
	2.69	2.58	2.92	2.53	2.21	2.43	2.19	2.18
102	21	12	23	12	24	12	15	12
	2.90	2.54	2.56	2.33	2.96	2.21	2.36	2.18
97	19	13	17	12	9	11	16	11
	2.35	2.44	1.93	2.28	2.51	2.22	1.88	2.07
92	10	12	12	12	13	12	14	11
	2.44	2.33	2.90	2.39	1.83	2.15	2.71	2.17
87	11	12	20	12	18	12	22	12
	2.42	2.48	2.98	2.13	2.29	2.23	1. 83	1.98

Subject 5
Age: 22
Weight: 78.5 kg
Height: 183.0 cm
Arm span: 186.8 cm

Height \ Length	17.5		20		22.5		25	
112	1	6	4	7	2	7	3	7
	2.84	2.26	2.93	2.49	1.83	2.13	2.91	2.07
107	6	8	7	8	5	8	8	8
	2.91	2.48	2.36	2.44	2.13	2.38	1.64	2.14
102	18	11	9	8	17	11	16	10
	1.57	2.45	2.77	2.47	1.03	2.17	2.98	2.01
97	22	12	24	11	21	10	14	9
	1.88	2.38	2.40	2.39	2.73	2.22	1.63	2.17
92	13	10	10	8	11	10	23	11
	2.31	2.45	2.70	2.37	1.66	2.28	2.93	2.31
87	19	11	20	10	12	10	15	10
	2.98	2.43	2.98	2.43	2.22	2.15	1.82	2.00

Subject 6
Age: 26

Weight: 75.3 kg
Height: 183.3 cm
Arm span: 185.5 cm

Length / Height	17.5		20		22.5		25	
112	3	13	2	13	4	13	1	13
	1.70	1.86	2.95	1.94	1.69	1.68	2.37	1.52
107	7	14	5	13	6	14	8	14
	1.97	1.51	2.94	1.67	2.17	2.23	1.74	1.56
102	9	14	17	16	24	17	21	16
	2.52	1.82	2.08	1.90	1.91	1.76	1.55	1.67
97	12	15	18	16	11	15	19	16
	2.00	1.79	2.00	1.74	1.25	1.64	1.75	1.60
92	16	16	15	16	22	17	14	15
	1.81	1.70	2.31	1.73	1.12	1.57	1.63	1.61
87	10	15	13	15	20	16	23	17
	2.78	1.67	1.38	1.52	1.68	1.66	1.73	1.67

Subject 7
Age: 24
Weight: 77.3 kg
Height: 185.8 cm
Arm span: 185.0 cm

Length / Height	17.5		20		22.5		25	
112	1	11	2	11	4	11	3	11
	1.92	1.65	2.17	1.88	1.94	1.71	1.09	1.43
107	7	12	8	12	6	11	5	12
	2.58	1.93	2.59	2.02	2.30	1.94	2.96	1.79
102	16	11	10	12	13	11	15	12
	2.24	1.98	2.78	1.98	2.55	1.95	2.33	1.73
97	18	13	22	11	20	11	21	11
	1.86	2.05	2.43	1.75	2.98	1.99	2.75	1.82
92	12	11	11	11	17	11	14	13
	2.62	1.87	2.97	1.94	2.52	1.94	1.52	1.75
87	19	12	23	13	9	12	24	14
	1.68	1.85	2.90	1.92	1.83	1.67	2.80	1.68

Subject 8
Age: 26
Weight: 81.8 kg
Height: 186.9 cm
Arm span: 185.5 cm

Height \ Length	17.5		20		22.5		25	
112	3	12	2	11	1	12	4	10
	2.25	1.81	2.90	1.90	1.88	1.79	1.65	1.39
107	8	13	7	12	5	8	6	9
	2.76	1.79	2.52	1.90	1.97	1.88	2.13	1.82
102	23	15	9	12	20	10	11	8
	2.04	2.08	2.16	1.97	2.05	1.80	2.08	1.70
97	24	15	19	13	18	12	22	9
	2.38	2.02	2.17	1.84	2.13	1.63	1.86	1.34
92	16	15	10	11	14	13	21	10
	2.98	1.85	2.97	1.83	2.62	1.74	2.02	1.61
87	13	12	17	13	12	9	15	8
	2.79	1.98	1.64	1.75	2.01	1.61	1.80	1.45