America's Cup Sailing: Biomechanics and conditioning for performance in grinding

Simon Pearson
BSc & MHSc (Hons)

A thesis submitted to the Auckland University of Technology in fulfilment of the degree of Doctor of Philosophy

November 2009

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ATTESTATION OF AUTHORSHIP

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the award of any other degree or diploma of a university or other institution of higher leaning, except where due acknowledgement is made in the acknowledgements.

Chapters 2 to 7 of this thesis represent six separate papers that have either been published or have been submitted to peer-reviewed journals for consideration for publication. My contribution and the contributed by the various co-authors to each of these papers are outlined at the beginning of each chapter. All co-authors have approved the inclusion of the joint work in this doctoral thesis.

Simon Pearson

November 2009

CANDIDATE CONTRIBUTIONS TO CO-AUTHORED PAPERS

Chapter publication reference	**Author %**
Chapter 2. Pearson SN, Hume PA, Slyfield D, Cronin JB. External work and peak power are reliable measures of ergometer grinding performance when tested under load, deck heel and grinding direction conditions. Sports Biomechanics. 2007; 6(1):71-80.	SP: 85% PH: 5% DS: 5% JC: 5%
Chapter 3. Pearson SN, Hume PA, Slyfield D, Cronin JB. Effects of pedestal orientation on grinding performance in America's Cup sailing. Journal of Sports Sciences. 2009; under review, November.	SP: 83% PH: 10% DS: 5% JC: 2%
Chapter 4. Pearson SN, Hume PA, Cronin JB, Slyfield D. America's Cup Sailing: Effect of grinding direction on EMG, kinematics, and torque application. Journal of Sports Sciences. 2009; submitted, November.	SP: 83% PH: 10% JC: 5% DS: 2%
Chapter 5. Pearson SN, Cronin JB, Hume PA, Slyfield D. Kinematics and kinetics of the bench press and bench pull exercises in a strength-training sporting population. Sport Biomechanics. 2009; 8(3):245–254.	SP: 83% JC: 10% PH: 5% DS: 2%
Chapter 6. Pearson SN, Cronin JB, Hume PA, Slyfield D. Strength and power determinants of grinding performance in America's Cup sailors. Journal of Strength and Conditioning Research. 2009; 23(6):1883-1889.	SP: 80% JC: 10% PH: 5% DS: 5%
Chapter 7. Pearson SN, Cronin JB, Hume PA, Slyfield D. Effects of a power-focussed resistance training intervention on backward grinding performance in America's Cup sailing. Sports Biomechanics. 2009; in press.	SP: 80% JC: 10% PH: 5% DS: 5%

ACKNOWLEDGEMENTS

Firstly I'd like to give my deepest thanks to my awesome supervisors, Patria and JC. You've been a constant source of advice, support and enthusiasm throughout what has been, at times, a somewhat challenging journey. I'm pretty sure I wouldn't have finished this without you. And more than, the amount of time and effort that both of you have given to me (and many of your other students) in an inspiration. Thank you.

David Slyfield: third supervisor, advisor, driver of the project, filter for stupid ideas and questions. Thanks for giving me the opportunity to work with you and Emirates Team New Zealand, and the time you put in to make it happen. It's been a great opportunity and something I've learnt a huge amount from, and I can only hope that you and the team got half as much out of this process as I did.

Thanks also to the sailors and support crew at Emirates Team New Zealand for their participation and assistance with this research. Also their feedback on the practical implications of the various studies for Americas Cup sailing, keeping this project grounded and practical.

Within AUT and the School of Sport and Recreation there are a number of people who have contributed to making this work. Thanks in particular to Professor Will Hopkins for his statistical advice at various stages along the road, and his endlessly useful spreadsheets. Also, thanks and apologies to anyone who's listened to me complain over the past few years.

I would like to acknowledge the Tertiary Education Commission (New Zealand), Emirates Team New Zealand and the Auckland University of Technology.

To my family: Mum and Dad, the support you've given me in various shapes and forms while I'm been completing this has been amazing, thank you so much.

And finally to my lovely wife Bronwen: thanks for your patience and the additional load you've had to take on at times while I've been trying to juggle work, study and everything else. There's one less thing to worry about now! Thank you so much for all your love and support.

Ethical approval

Ethical approval for this research was granted by the Auckland University of Technology Ethics Committee (AUTEC). The AUTEC reference was 04/221, with approval granted originally on the 20 December 2004 and extended 27 November 2006.

ABSTRACT

Grinding is integral to tacking and gybing manoeuvres in America's Cup sailing. Grinding is a standing position cyclic upper body task requiring manual arm cranking of winches, which control movement of the mast and sails. Limited information exists on biomechanical factors involved in grinding performance. This thesis determined technique and muscular performance characteristics of sailors related to grinding performance, and effects of a training intervention on grinding performance.

Reliability of grinding ergometer performance testing was evaluated across direction, load and heel conditions. In all conditions relative performance between individuals was consistent (r = 0.84-0.99) and the grinding performance test differentiated well between individuals. External work had lower overall variation (1.6-3.9%) than peak power (1.3-5.4%), especially when grinding against greater loads. Grinding performance was less consistent in heeled conditions (4.6-6.9%) than on the flat, but grinding direction did not affect reliability. Performance changes over 4% could be interpreted with confidence.

Peak torque occurred at 95° (77 N m) and 35° (69 N m) for forward and backward grinding respectively (0° = grinding crank vertically up). Torque of >50 N m was maintained through 72% of the cycle during forward grinding but only 47% for backward grinding. Differences were attributed to a greater spread of active muscles throughout the cycle for forward grinding, and contrasting movements contributing most to torque – upper body push for forward grinding and pull for backward grinding. Variant characteristics of the two grinding directions provide some explanation for the significant advantage (+8.0%, $p<0.001$) when grinding in pairs with an anterior-posterior heel compared to a medio-lateral heel. Movement characteristics did not readily explain why an anterior-posterior heel may be more advantageous under higher grinding loads (1.0%, $p = 0.254$), while medio-lateral heel is better at lower loads (2.0%, $p = 0.017$).

Muscular performance of sailors, examined using an instrumented Smith machine, showed force and 1RM strength were greater in the bench press by ~17%. Velocity and power output were greater for the bench pull across the range of loads with the difference increasing exponentially as load increased to over 400% higher at 1RM load. Bench press 1RM and maximum force capability demonstrated strongest correlations with forward grinding performance (r = 0.88-0.99 and 0.87-0.99 respectively) with the relationship increasing with grinding load. There was a strong relationship for backward grinding with bench pull maximum power (r = 0.85-0.98) in addition to 1RM (r = 0.90-0.95) and maximum force (r = 0.87-0.95).

Backward grinding performance showed greater improvements in the power-focussed training group than the control group for moderate (+1.8%) and heavy load (+6.0%) grinding in the intervention study. Changes in maximum power output and power at 1RM had large correlations (r = 0.56-0.61) with changes in both moderate and heavy load grinding performance. Time to peak force explained 70% of the change in heavy load grinding performance. Performance benefits from the training intervention were not entirely clear, but the likelihood of a detrimental effect was low (<5%), therefore further training intervention was recommended.

RESEARCH PUBLICATIONS RESULTING FROM THIS DOCTORAL THESIS

Section 1: Reliability of grinding ergometer

Chapter 2: External work and peak power are reliable measures of ergometer grinding performance when tested under load, deck heel and grinding direction conditions.

Pearson SN, Hume PA, Slyfield D, Cronin JB. External work and peak power are reliable measures of ergometer grinding performance when tested under load, deck heel and grinding direction conditions. Sports Biomechanics. 2007; 6(1):71-80.

(Author contribution percentages: SP: 88%, PH: 5%, DS: 5%, JC: 2%).

Chapter 2 appendix (Appendix 1):

Pearson SN, Hume PA, Cronin JB, Slyfield D. Test-retest reliability of selected grinding ergometer measures for sailing performance. In: Schwameder H, Strutzenberger G, Fastenbauer V, Lindinger S, Muller E, editors. XXIV International Symposium on Biomechanics in Sports; 2006 July 14-18; Salzburg, Austria: Department of Sport Science and Kinesiology, University of Salzburg; 2006. p. 546-9.

(Author contribution percentages: SP: 88%, PH: 5%, JC: 5%, DS: 2%).

Section 2: Grinding biomechanics

Chapter 3: Effects of pedestal orientation on grinding performance in America's Cup sailing.

Pearson SN, Hume PA, Slyfield D, Cronin JB. Effects of deck heel (tilt) on grinding performance in America's Cup sailing. Journal of Sport Sciences. 2009; under review, November.

(Author contribution percentages: SP: 83%, PH: 10%, DS: 5%, JC: 2%).

Chapter 3 appendix (Appendix 2):

Pearson SN, Hume PA, Cronin JB, Slyfield D. Grinding simulator tilt study report. Auckland, NZ: Institute of Sport and Recreation Research New Zealand, Auckland University of Technology; 2005 March. 6 pages.

(Author contribution percentages: SP: 83%, PH: 10%, JC: 5%, DS: 2%).

Chapter 4: America's Cup sailing: Effect of grinding direction on EMG, kinematics, and torque application.

Pearson SN, Hume PA, Cronin JB, Slyfield D. America's Cup Sailing: Effect of grinding direction on EMG, kinematics, and torque application. Journal of Sports Sciences. 2009; submitted, November.

(Author contribution percentages: SP: 83%, PH: 10%, JC: 5%, DS: 2%).

Chapter 4 appendix (Appendix 3):

Pearson SN, Hume PA, Cronin JB, Slyfield D. The influence of technique on grinding performance. A technical report for Emirates Team New Zealand. Auckland: Institute of Sport and Recreation Research New Zealand, Auckland University of Technology; 2006 June. 20 pages.

(Author contribution percentages: SP: 83%, PH: 10%, JC: 5%, DS: 2%).

Chapter 4 appendix (Appendix 4):

Pearson SN, Hume PA, Cronin JB, Slyfield D. Biomechanical characteristics of grinding in America's Cup sailing. In: Harrison D, Anderson R, Kenny I, editors. XXVII International Conference on Biomechanics in Sports Proceedings; 2009 17-21 August; University of Limerick, Limerick, Ireland; 2009. p. 694.

(Author contribution percentages: SP: 85%, PH: 10%, JC: 3%, DS: 2%)

Section 3: Physical conditioning

Chapter 5: Kinematics and kinetics of the bench press and bench pull exercises in a strength-trained sporting population.

Pearson SN, Cronin JB, Hume PA, Slyfield D. Kinematics and kinetics of the bench press and bench pull exercises in a strength-training sporting population. Sport Biomechanics. 2009 September; 8(3):245–54.

(Author contribution percentages: SP: 83%, JC: 10%, PH: 5%, DS: 2%)

Chapter 5 appendix (Appendix 5):

Pearson SN, Cronin JB, Hume PA, Slyfield D. Kinematics and kinetics of the bench press and bench pull exercises in a strength-trained sporting population. In: Menzel H-J, Chagas MH, editors. XXV International Symposium on Biomechanics in Sports Proceedings; 2007 23-27 August; Federal University of the State of Minas Gerais in Belo Horizonte, Ouro Preto, Brazil; 2007. p. 470-3.

(Author contribution percentages: SP: 83%, JC: 10%, PH: 5%, DS: 2%)

Chapter 5 appendix (Appendix 6):

Pearson SN, Cronin JB, Hume PA, Slyfield D. Bench press versus bench pull – kinematics, kinetics and 1RM determination. Sports Medicine and Sport Science and Exercise Science New Zealand Conference; 2007 November Hamilton; 2007. p. 74.

(Author contribution percentages: SP: 83%, JC: 10%, PH: 5%, DS: 2%)

Chapter 6: Strength and power determinants of grinding performance in America's Cup sailors.

Pearson SN, Cronin JB, Hume PA, Slyfield D. Strength and power determinants of grinding performance in America's Cup sailors. Journal of Strength and Conditioning Research. 2009; 23(6):1883-1889.

(Author contribution percentages: SP: 80%, JC: 10%, PH: 5%, DS: 5%)

Chapter 6 appendix (Appendix 7):

Pearson SN, Cronin JB, Hume PA. Results of power the profiling study. Technical report to Emirates Team New Zealand. Auckland, NZ: Institute of Sport and Recreation Research New Zealand, Auckland University of Technology; 2006 May 2006. 6 pages.

(Author contribution percentages: SP: 80%, JC: 10%, PH: 10%)

Section 4: Power intervention

Chapter 7: Effects of a power-focussed resistance training intervention on backward grinding performance in America's Cup sailing.

Pearson SN, Cronin JB, Hume PA, Slyfield D. Effects of a power-focussed resistance training intervention on backward grinding performance in America's Cup sailing. Sports Biomechanics. 2009; in press.

(Author contribution percentages: SP: 80%, JC: 10%, PH: 5%, DS: 5%).

Chapter 7 appendix (Appendix 8):

Pearson SN, Cronin JB, Hume PA. Backward grinding performance and rep tempo in weight training. A technical report for Emirates Team New Zealand: Institute of Sport and Recreation Research New Zealand, Auckland University of Technology; 2007 June. 8 pages.

(Author contribution percentages: SP: 80%, JC: 10%, PH: 10%)

CHAPTER 1

INTRODUCTION AND RATIONALISATION (PREFACE)

Background

The America's Cup is generally regarded as the most prestigious competition in sailing and is the oldest trophy in international sport, however, until recently there has has been very little published research on this event. On-water performance in America's Cup competition is determined by numerous factors including tactics, crew work and yacht design, however, in terms of physical human performance during racing, grinding (which controls the movement of the mast and sails) is considered to be the primary physical activity [1] and therefore of most interest from a sport science perspective.

When we were approached by the Emirates Team New Zealand America's Cup syndicate at the initiation of this body of research there was virtually no available scientific research into the factors affecting grinding performance. Publications on the topic were limited to nutritional requirements [2], physiological characteristics [3], and anthropometric description [4] of the various positional roles within an America's Cup crew. In terms of specific work on grinding there was only an investigation into how changes in body position could be used to improve performance, conducted as this authors' Master's research [5]. The success of that project in improving grinding performance in some sailors contributed sport-specific rationale that research to better understand the grinding activity could be used to improve grinding performance and therefore contribute to on-water success.

This led to the formulation of the central theme of this thesis: To increase understanding of the biomechanical requirements of grinding in order to advise technique and conditioning practices and enhance grinding performance.

Structure

The thesis is structured as a series of related chapters (see Figure 1) that culminate in an overall discussion (Chapter 8). Most of these chapters have been submitted for publication in journals or for conference presentations, which has allowed the author to gain international peer reviewed feedback on the content, which has improved the chapters. Technical reports have also been provided to Emirates Team New Zealand to provide them with feedback useful for their programme, and to gain their feedback to aid in development of projects for later chapters.

The first thematic section of the thesis (Chapter 2) focused on the reliability of grinding ergometer performance and was a central component to the research as the principal means of relating findings to on-water performance. It was established that both external work performed and peak power were reliable measures of ergometer grinding performance when tested under load, deck heel and grinding direction conditions. Publications resulting from Chapter 2 were:

Pearson SN, Hume PA, Slyfield D, Cronin JB. External work and peak power are reliable measures of ergometer grinding performance when tested under load, deck heel and grinding direction conditions. Sports Biomechanics. 2007; 6(1):71-80.

Pearson SN, Hume PA, Cronin JB, Slyfield D. Test-retest reliability of selected grinding ergometer measures for sailing performance. In: Schwameder H, Strutzenberger G, Fastenbauer V, Lindinger S, Muller E, editors. XXIV International Symposium on Biomechanics in Sports; 2006 July 14-18; Salzburg, Austria: Department of Sport Science and Kinesiology, University of Salzburg; 2006. p. 546-9.

The second thematic section of the thesis (Chapters 3-4) examined how different factors affected the performance and biomechanics of grinding. While there was little effect of tilt direction during individual grinding, anterior-posterior (in-line) tilt was more advantageous for paired grinding. Biomechanical characteristics of grinding differed greatly between forward and backward grinding, which was likely to be a contributing factor in the performance effects in the tilt study. Publications that resulted from Chapters 3-4 were:

Pearson SN, Hume PA, Slyfield D, Cronin JB. Effects of pedestal orientation on grinding performance in America's Cup sailing. Journal of Sport Sciences. 2009; under review, November.

Pearson SN, Hume PA, Cronin JB, Slyfield D. America's Cup Sailing: Effect of grinding direction on EMG, kinematics, and torque application. Journal of Sports Sciences. 2009; under review, November.

Pearson SN, Hume PA, Cronin JB, Slyfield D. Grinding simulator tilt study report. Auckland, NZ: Institute of Sport and Recreation Research New Zealand, Auckland University of Technology; 2005 March 2005. 6 pages.

Pearson SN, Hume PA, Cronin JB, Slyfield D. The influence of technique on grinding performance. A technical report for Emirates Team New Zealand. Auckland: Institute of Sport and Recreation Research New Zealand, Auckland University of Technology; 2006 June. 20 pages.

Pearson SN, Hume PA, Cronin JB, Slyfield D. Biomechanical characteristics of grinding in America's Cup sailing. In: Harrison D, Anderson R, Kenny I, editors. XXVII International Conference on Biomechanics in Sports Proceedings; 2009 17-21 August; University of Limerick, Limerick, Ireland; 2009. p. 694.

The third thematic section of the thesis (Chapters 5-6) that focused on physical conditioning found that kinematics and kinetics were significantly different for upper body push (bench press) and pull (bench pull) movements, and that the elements of muscular performance related to grinding performance differed with grinding direction (forward or backward). Publications that resulted from Chapters 5-6 were:

Pearson SN, Cronin JB, Hume PA, Slyfield D. Kinematics and kinetics of the bench press and bench pull exercises in a strength-training sporting population. Sport Biomechanics. 2009 September; 8(3):245–54.

Pearson SN, Cronin JB, Hume PA, Slyfield D. Strength and power determinants of grinding performance in America's Cup sailors. Journal of Strength and Conditioning Research. 2009; 23(6):1883-1889.

Pearson SN, Cronin JB, Hume PA, Slyfield D. Kinematics and kinetics of the bench press and bench pull exercises in a strength-trained sporting population. In: Menzel H-J, Chagas MH, editors. XXV International Symposium on Biomechanics in Sports Proceedings; 2007 23-27 August; Federal University of the State of Minas Gerais in Belo Horizonte, Ouro Preto, Brazil; 2007. p. 470-3.

Pearson SN, Cronin JB, Hume PA, Slyfield D. Bench press versus bench pull – kinematics, kinetics and 1RM determination. Sports Medicine and Sport Science and Exercise Science New Zealand Conference; 2007 November Hamilton; 2007. p. 74.

Pearson SN, Cronin JB, Hume PA. Results of the power profiling study. Technical report to Emirates Team New Zealand. Auckland, NZ: Institute of Sport and Recreation Research New Zealand, Auckland University of Technology; 2006 May 2006. 6 pages.

The final thematic section of the thesis (Chapter 7) took the lessons learnt from the prior studies and involved a training intervention to improve grinding performance. The experimental study determined the effects of a power-focussed resistance training intervention on backward grinding performance in America's Cup sailing. The intervention showed that placing greater emphasis on the velocity component of the strength-training stimulus produced greater benefits for grinding performance than conventional (normal speed) training. The publications that resulted from Chapter 7 were:

Pearson SN, Cronin JB, Hume PA, Slyfield D. Effects of a power-focussed resistance training intervention on backward grinding performance in America's Cup sailing. Sports Biomechanics. 2009; in press.

Pearson SN, Cronin JB, Hume PA. Backward grinding performance and rep tempo in weight training. A technical report for Emirates Team New Zealand: Institute of Sport and Recreation Research New Zealand, Auckland University of Technology; 2007 June. 8 pages.

Chapter 8 consists of a general discussion of findings from the presented research projects, comments on limitations to the research studies, provides areas for future research, and provides some concluding statements on the key findings from the thesis.

The appendices contain material for chapters 2-7 that were presented as technical reports to Emirates Team New Zealand or as conference presentations. A sample subject information pack and consent form are provided in Appendix 9 and 10. Appendices 11 and 12 are notifications from the Auckland University of Technology Ethics Committee (AUTEC) regarding ethical approval where required.

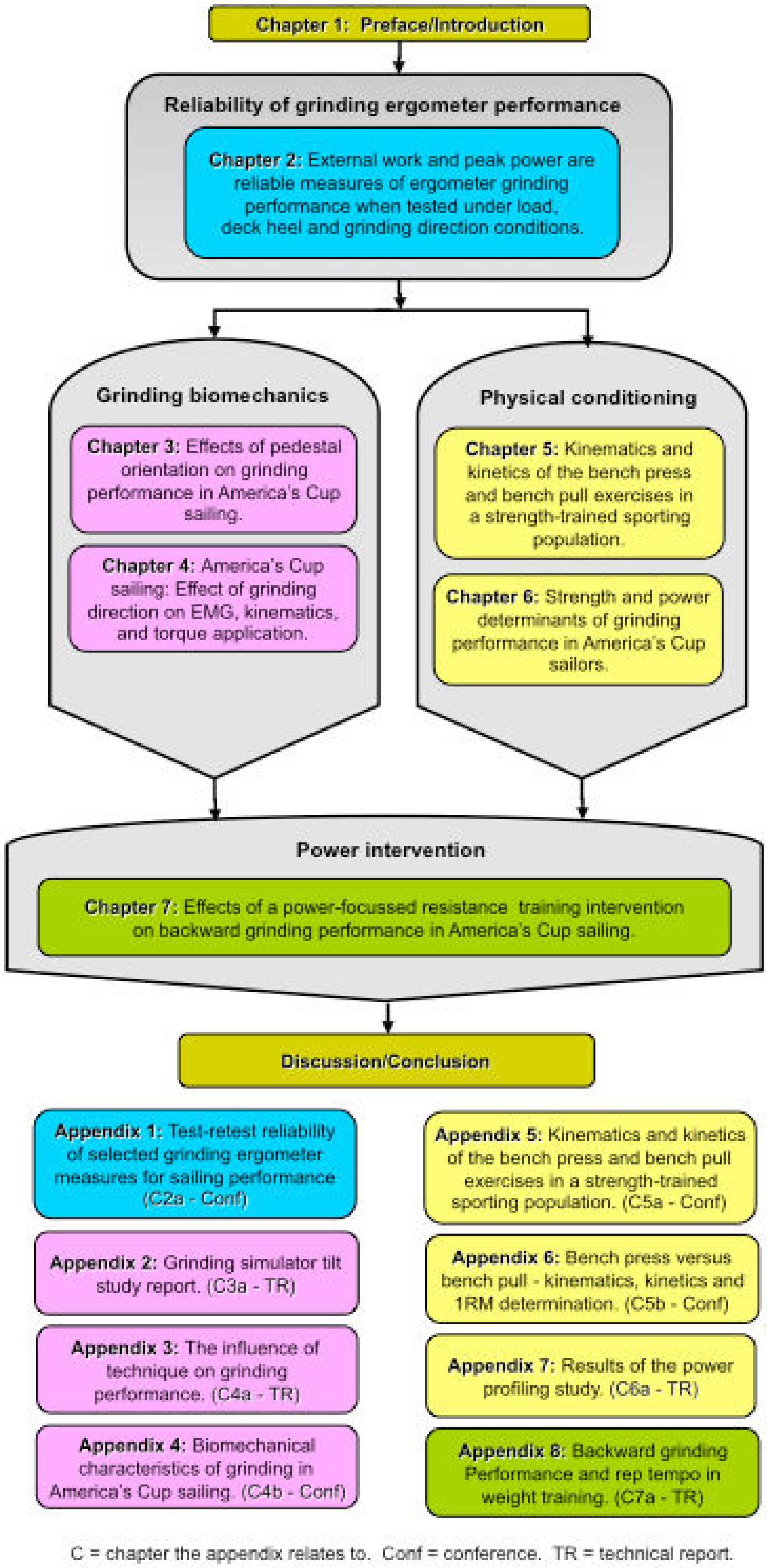


Figure 1: Overview of doctoral thesis chapter flow.

CHAPTER 2

EXTERNAL WORK AND PEAK POWER ARE RELIABLE MEASURES OF ERGOMETER GRINDING PERFORMANCE WHEN TESTED UNDER LOAD, DECK HEEL AND GRINDING DIRECTION CONDITIONS

This chapter comprises the following paper accepted by *Sports Biomechanics*:

Pearson SN, Hume PA, Slyfield D, Cronin JB. External work and peak power are reliable measures of ergometer grinding performance when tested under load, deck heel and grinding direction conditions. Sports Biomechanics. 2007; 6(1):71-80.

(Author contribution percentages: SP: 88%, PH: 5%, DS: 5%, JC: 2%).

OVERVIEW

The reliability of grinding performance was assessed on a custom-built ergometer using two testing sessions separated by five hours for eighteen current Emirates Team New Zealand America's Cup sailors. Sixteen different grinding conditions varied by load (light 39 N m, moderate 48 N m, heavy 68 N m), deck heel (Flat 0° control, Downhill 25°, Uphill 25°, Right 25°, Left 25°), and grinding direction (forwards, backwards), were assessed using peak power (W) and external work over five seconds (kJ) during maximal effort eight-second grinds. Reliability statistics were difference in mean (M_{diff}), standard error of measurement (SEM) and intra-class correlation coefficients (ICC). External work (SEM = 1.6-6.9%; ICC = 0.91-0.99) was a more consistent performance measure than peak power (SEM = 1.3-9.6%; ICC = 0.84-0.99) across all testing conditions. Testing under different load conditions resulted in external work SEM's of 1.6-3.9% with performance more reliable in lighter load conditions. Grinding performance during different heel conditions was less reliable - external work SEM's = 4.6-6.9%. Grinding direction (forward or backward) did not appear to affect performance reliability although external work was 10-15% higher in forward grinding. Reliability is at an acceptable level across a variety of loads, but testing under different heel conditions may need some protocol development to allow detection of smaller differences in performance.

INTRODUCTION

Grinding performance in America's Cup racing is an important determinant of overall boat speed. The grinding winches are responsible for the movement of the sails and therefore provide the power behind tacking and gybing, where the yacht crosses the wind to change direction. In addition the grinding winches are used for trimming the sails, which changes the angle on which the yacht is headed and the efficiency of wind usage. As such, much time and effort is spent on equipment design and testing, technique training and conditioning of the grinders. To monitor the effects of various technique changes, training schemes or other performance enhancing interventions, a custom-built instrumented grinding ergometer (Dynapack, Wellington, New Zealand) was constructed for the purpose of providing an easy, land-based method of assessment of grinding performance. As with any new piece of equipment or procedure to be used in this manner it is necessary to determine the validity and repeatability of testing results.

In terms of validity, it is important that both the equipment and the measures used to quantify performance are appropriate for the task being assessed. The grinding ergometer constructed used standard on-board grinding hardware to ensure familiarity for the sailors involved. The dynamometer used was subjectively assessed by the sailors to have the same "feel" as the on-board system and preliminary results were consistent with previous research into grinding performance using an older model ergometer [5].

As on-water grinding performance is determined in part by the time taken to pull in a sail line against a certain load, it was necessary to assess ergometer performance using an appropriate measure. Power output against a set load gives the most valid assessment of grinding performance, with power for a cyclic movement defined by Hull and Gonzalez (1988) as the product of applied force, length of the crank arm and angular velocity of the movement ($P = F \times L \times \omega$). Peak power (W) corresponds to the fastest speed at which sail line can be pulled in against a certain load, while the external work performed (kJ) over a certain period relates to the total amount of sail line able to be pulled in during that time period. Mean power is another measure often used in studies of this nature, although in this instance mean power and external work over a set time period will yield essentially the same result. External work (total line pulled in) was therefore deemed to be a more appropriate measure. However, appropriate/valid measures of performance are only useful provided the testing protocols used are also reliable.

When assessing the reliability of a testing procedure it is important that the assessment be as specific as possible to race conditions as there may be a number of factors that may alter the level and consistency of performance. Grinding performance has been previously found to be influenced by conditions such as grinding direction and system resistance [5], and sailors reported that performance may also be influenced by deck heel (tilt). In terms of grinding direction, the sailor may either grind forward – pushing away from the trunk at the top of the rotation; or backward – pulling towards the trunk at the top of the rotation, depending on what gear the winches are in. System resistance and deck heel are both products of wind strength and boat heading. System resistance (load on the grinding winches) increases with wind strength and sail position relative to wind direction, while heel is the sideways lean of the yachts' deck when sailing up-wind, which can increase up to 25-30° with wind strength. Variations in grinding direction and system loading are frequent during competition sailing and therefore land-based testing must monitor performance under these different conditions. Deck heel was included in this study as the influence of deck-layout on grinding performance was an area of research interest for the Emirates Team New Zealand syndicate. In particular, any differences in performance between grinding pedestals orientated fore-aft (resulting in left-right/bi-directional lateral tilt when grinding under heel conditions), and pedestals orientated across the boat (downhill-uphill/anterior-posterior tilt when grinding under heel) were of interest to the boat designers.

Quantifying the normal trial to trial performance variation in grinding for each of these conditions is essential for monitoring performance. To conclude whether a real change in performance has been produced by an intervention, the change must be greater than the normal repeated trial variation under the same conditions, or reliability of the test. A reliable test is considered to be one with small changes in the mean, a low standard error of measurement (SEM) and a high test-retest correlation between repeated trials [6]. The purpose of this study therefore was to determine the reliability of both forward and backward grinding performance in a range of different load and heel conditions on a newly constructed grinding ergometer.

METHODS

Ergometer testing was divided into two rounds (Load, Heel) on separate days for the effects on reliability of peak power (W) and external work over five seconds (kJ) for both forward and backward grinding. All procedures used in this study complied with the guidelines of the Auckland University of Technology Ethics Committee.

Subjects

Male America's Cup sailors who performed grinding routinely participated in this study; 18 completed load testing and 9/18 completed heel testing (due to availability). The sailors' characteristics are outlined in Table 1.

Table 1: Sailor characteristics for each of the testing rounds.

	Round 1: Load		**Round 2: Heel**
Load	*Light/Moderate*	*Heavy*	
Sailors (number)	18	6	9
Age (years)	34.8±5.7	33.7±5.5	32.7±5.5
Height (cm)	183.3±7.4	189.8±6.8	185.3±7.5
Mass (kg)	92.8±12.7	105.6±10.6	94.2±13.7
Lean mass (kg)	80.3±11.2	91.7±8.7	81.7±12.5

Equipment

The experimental setup consisted of a grinding ergometer with standard pedestal (870 mm vertical) and crank arm (250 mm) dimensions for a main sheet grinding pedestal on an America's Cup class yacht (see Figure 2). Gearing for the ergometer was linked through a multiple-speed dynamometer set up to output a number of grinding performance measures. Power output was obtained from the grinding ergometer using a bi-directional oil hydraulic system custom designed to meet the tactile characteristics of the rigging at the grinding station. Speed was based on a 24-slot disc attached directly to the motor input shaft. Output was obtained via an analogue to digital converter using 8-bit resolution to a C++ customised data collection system sampling at 40 Hz. Mechanical load was varied using a custom designed cog selector allowing 1:1 and 3:1 ratios driven by toothed belts. Hydraulic load was applied using a dynamic closed loop controller modified to operate at low speed. Calibration was performed using calibrated masses and known lever lengths, and the machine was verified accurate to 0.5% or better throughout its range.

Figure 2: Images of the grinding ergometer positioned flat (left) and at 25° anterior-posterior tilt (right).

Procedures

Anthropometric descriptors

All participating sailors were measured for standing height, body mass, eight skinfolds, five muscle girths, and two bone breadths using the International Society for the Advancement of Kinathropometry (ISAK) protocols for a restricted profile [7]. Lean muscle mass was calculated using the methods of Sloan and Weir [8].

Grinding testing protocols

For both heel and load conditions, the sailors completed a self-determined warm-up on the grinding ergometer prior to testing. Each testing session consisted of a single trial of all relevant load or heel conditions. All grinding trials were maximal effort, eight-seconds in length, and separated by a 3-5 minute rest period. Verbal "go" and "stop" signals were the only in-trial feedback. For each round (load or heel), the protocols were repeated 5 hours apart.

Round 1: Load testing

Both forward and backward grinding were tested using three torque loading conditions; 39 N m (Light), 48 N m (Moderate), and 68 N m (Heavy). Testing loads were selected to mimic high-low- and moderate-load conditions during on-water grinding manoeuvres, based on rpm ranges for a primary grinder. All 18 sailors completed the light and moderate loads but due to the physical requirements for grinding effectively at the heavy load only the six sailors regarded as primary grinders (i.e., their main on-board responsibility is grinding) completed the heavy load condition. Load conditions were randomised, with trials alternating between forward and backward grinding to reduce the possible influence of any order or fatigue effects. The session was completed in 40 minutes.

Round 2: Heel testing

Forward and backward grinding performance of nine of the eighteen sailors was tested for five heel conditions:

Flat: 0° control.

Downhill: Grinding from above the pedestal with 25° deck heel.

Uphill: Grinding from below the pedestal with 25° deck heel.

Right: Grinding with right-hand side of the body on the high-side of the pedestal with 25° deck heel.

Left: Grinding with left-hand side of the body on the high-side of the pedestal with 25° deck heel.

All ten conditions were against the same constant load of 45 N m. The 25° angle was selected as an upper range heel angle experienced in racing conditions, and angles for the ergometer platform were verified using a SmartTool™ digital spirit level (M-D Building Products, Oklahoma, USA). Heel condition order was randomised to reduce order effects, with trials alternating between forward and backward grinding to reduce the influence of fatigue. The session was completed in 60 minutes.

Data Analyses

The measure of interest to this study was power output (W), which could be used to quantify performance in terms of peak power (W) and external work over a period of time (kJ). Raw power values were calculated by the Dynapack ergometer software using the formula: Power (W) = Torque x (2π*rpm)/60. The raw power curve was then smoothed using a second order recursive Butterworth low pass filter, and peak power and external work calculated using a customised Labview program. Peak power is an instantaneous maximum value identified from the smoothed data. External work performed is the five-second integral of the area under the power curve, starting at the occurrence of peak power (see Figure 3).

Statistical analyses

Descriptive statistics for all variables are represented as mean and standard deviations (spread of results among participants). Only one trial was recorded for the repeated backward, light-load testing for six of the 18 sailors due to a computer recording error. These data were included for descriptive statistics but excluded for reliability measures. Measures of reliability (difference in mean, standard error of measurement and intra-class correlation coefficients) were determined using a repeated measures analysis of variance. Data were log transformed for external work (kJ) and peak power (W) to provide measures of reliability as standard error of measurement (SEM) and intra-class correlation coefficients (ICC) were calculated [9]. The presence of significant systematic discrepancy between reliability measures of different grinding conditions was determined using a two-tailed unpaired *t*-test.

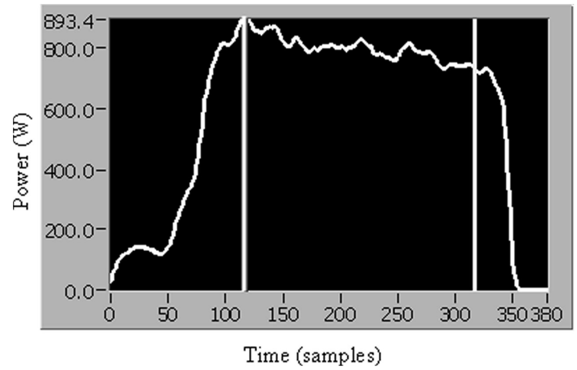


Figure 3: **An example power output trace from a complete trial. Vertical markers indicate peak power, and five seconds post peak power.**

RESULTS

Reliability of testing at different loads

There were small changes in the group means for peak power output and external work performed under all directional and loading conditions (see Table 2). The SEM was similar for external work performed and peak power in all conditions (average SEM = 3.1 and 3.3% respectively) but less variation was observed for external work (1.6-3.9%) than peak power (1.3-5.4%). SEM tended to increase with load for both forward and backward grinding. The smallest SEM for both external work and peak power was recorded during the light-load backward condition followed by the light-load forward condition. With the exception of the heavy-load forward condition (0.84), all the test-retest intra-class correlation coefficients were ≥ 0.91.

Table 2: **Mean (± standard deviation) peak power and external work for grinding performance during different load conditions with the corresponding expected difference in mean (Mdiff) between repeated trials, standard error of measurement (SEM) and intra-class correlation coefficients (ICC).**

Grinding condition	*Test 1* Mean ± SD	*Test 2* Mean ± SD	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

Note: n=18 sailors except n=6 for heavy load conditions.

Reliability of testing with different heel directions

Between-test differences in mean peak power and mean external work were larger for heel direction testing (0 to 4.3%) than for load testing (0.1 to 2.1%). The SEM was lower for external work than peak power in seven of the ten conditions, and was also lower on average (external work = 5.5%, peak power = 6.1%). External work SEM (4.6-6.9%) was again more consistent than peak power SEM (3.5-9.6%). SEM was significantly (p < 0.05) greater in right-left/medio-lateral heel conditions than uphill-downhill/anterior-posterior heel conditions for both peak power (p = 0.028) and external work (p = 0.030) (see Table 3). The test-retest intra-class correlation coefficients were all 0.92 or greater.

Table 3: Mean (± standard deviation) peak power and external work for grinding performance during different heel conditions with the corresponding expected difference in mean (M_{diff}) between repeated trials, standard error of measurement (SEM) and intra-class correlation coefficients (ICC). N = 9 sailors.

Grinding condition	*Test 1* Mean ± SD	*Test 2* Mean ± SD	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

DISCUSSION AND IMPLICATIONS

For a performance test to be valuable it must be specific enough to be measuring the performance variable of interest but also reliable enough to detect the relatively small differences in performances that are beneficial to elite athletes [10]. This study quantified the variability in grinding performance under different load, direction, and heel conditions, with the main measures of interest, in terms of reliability, being the standard error of measurement (SEM) and the intraclass correlation coefficient (ICC).

Reliability of performance at different loads

Variation in grinding performance was small across all load conditions, with the least variation observed with light load backward grinding (SEM: peak power = 1.3, external work = 1.6) and the least reliable being heavy load forward grinding (SEM: peak power = 5.4, external work = 3.7). Performance became increasingly more variable in both forward and backward grinding as load increased. A similar pattern was seen in the ICC's with the relative consistency of performance between individuals decreasing as load increased. An additional factor in this study which affected the apparent variability at heavier load grinding was the number of subjects completing the trials at the heavy load (n = 6) compared to the moderate and light loads. As the heavy load trials only included the most accomplished grinders the standard deviation for the heavy load conditions was lower than for the moderate load conditions, however, the low statistical power associated with low subject numbers leads to a higher SEM. Nevertheless, based on current results a change in external work of over 4% or a change in peak power of over 5.5% can be interpreted with a fair degree of certainty under any loading condition.

Reliability of performance at different heel angles

Testing at different heel angles was considerably more variable than at different loads on a flat 0° heel. Although the repeated trial difference in the mean was never more than 5% for any heel condition, SEM varied from 3.5% (forward grinding from below at 25°) to 9.6% (backward grinding, right-hand side high at 25°) for peak power and between 4.6% (backward grinding at 0°) and 6.9% (forward grinding, right-hand side high at 25°) for external work. It would seem that performance changes can only be interpreted with any confidence if they are over 7% for external work or 10% for peak power. While in some circumstances a standard error of measurement of under 10% may be considered small [11], it is important to interpret levels of error in their relevant context. In the case of America's Cup grinding performance a level of closer to 5% is more appropriate as performance changes at an elite level are likely to be relatively small. For example, previous grinding research [5] documented a 4.7% (p = 0.012) performance increase from a group of sailors following a technique intervention, giving an indication of the magnitude of changes that could be expected in this population.

The generally higher variability in the heel testing compared to the load testing is likely to be a result of a reduction in base of support stability when shifting from a flat to a tilted surface, resulting in increased variability in performance. However, it is also possible that reliability could be improved with adaptations to the testing protocol. The heel testing sessions involved 10 maximal grinds at a moderately heavy load making it a more intensive session than for the load testing (six varied load grinds) due to the volume of work performed. It is possible that by altering how many grinds are performed in a session and/or altering recovery time we may be able to reduce the influence of fatigue and therefore performance variability. This view is supported by the greater variability in both the forward and backward flat conditions within the heel testing when compared to a similar condition in the load testing (forward and back, moderate load) where grinders performed only four to six maximal grinds. It is possible that the influence of fatigue, either physiological or mental, from the longer testing session may have affected performance reliability.

Peak power versus external work as a performance measure

It is apparent from the results that while there is little difference in reliability between external work (kJ) and peak power (W) when grinding load and direction are varied, peak power is substantially less reliable when deck heel is involved. While there was little difference between the ICC values overall, only five of the total 16 conditions tested had a lower level of absolute variability (SEM) in peak power than external work. Although this finding is at odds with a number of studies investigating the reliability of peak power and external work in cycling [12-13], an activity with substantial mechanical similarities to grinding, it is consistent with studies investigating power output in various upper and lower body exercises such as bench press and isokinetic leg press [14-15]. Some of the discrepancy in these findings can be attributed to the method of peak power calculation, as instantaneous peak values, such as those used in the present study, are inherently less stable than averaged values. However, it should be noted that the studies providing evidence of peak power as a more reliable measure than external work were largely basing their conclusions on correlations, which can be inappropriate and misleading in studies on reliability [16], especially when dealing with muscular strength [17]. While a high correlation indicates good repeatability in terms of relative rankings, the ability to accurately quantify absolute changes in performance is generally more important when examining the effect of any kind of intervention. Therefore, while peak power is still a relevant measure and is still worth assessing, external work seems a more reliable means of quantifying grinding performance based on the results of this study. External work is more appropriate for assessment of grinding performance than peak power as it is important to the performance of the boat for power output to be maintained over a period of time.

Influence of grinding direction

While there is commonly a 10-15% decrement in both peak power and external work for backward grinding when compared to forward grinding, there does not appear to be any systematic difference in the reliability of performance according to grinding direction.

CONCLUSIONS

External work appears more reliable than peak power as a means of quantifying grinding performance, although peak power may still be useful in flat heel conditions. Using current protocols the SEM for external work was up to 4% in different load conditions and up to 7% for heel conditions. A change of 5-10% in grinding performance would be considered substantial and therefore it would be beneficial to improve the precision of measurement, especially in terms of heel condition testing, in order to be confident of detecting changes of a smaller magnitude. External work is more appropriate for assessment of grinding performance than peak power as it is important to the performance of the boat for power output to be maintained over a period of time.

PRACTICAL IMPLICATIONS

Emirates Team New Zealand has used the results of this study to determine their testing protocols for grinding ergometer performance. When assessing intervention effectiveness, the ergometer grinding protocol consists of no tilt, forward and backward grinding at three load levels. External work derived as a five second interval of power starting from peak power, is used to quantifying grinding performance. Improvements in external work over 4% are considered to be beyond the expected variation for repeated tests.

CHAPTER 3

EFFECTS OF PEDESTAL ORIENTATION ON GRINDING PERFORMANCE IN AMERICA'S CUP SAILING

This chapter comprises the following paper that has been submitted to *Journal of Sports Sciences*:

Pearson SN, Hume PA, Slyfield D, Cronin JB. Effects of pedestal orientation on grinding performance in America's Cup sailing. Journal of Sport Sciences. 2009 under review, November.

(Author contribution percentages: SP: 83%, PH: 10%, DS: 5%, JC: 2%).

OVERVIEW

This study compared the effects of pedestal orientation in heel conditions on America's Cup grinding performance. A custom-built ergometer was used to assess grinding performance (eight-second maximal effort) of twelve male America's Cup sailors using both a "conventional" (lateral tilt) and an "in-line" (anterior-posterior tilt) pedestal orientation relative to deck heel, along with a "flat" control condition. Testing was performed both as individuals and in pairs (two sailors working together). Performance for all conventional and in-line conditions was significantly worse ($p<0.05$) than grinding on the flat. There was little difference between conventional and in-line configurations during individual testing (conventional +0.6%, $p = 0.355$) but a significant bias to the in-line system during paired testing (+8.0%, $p<0.001$). This difference was likely due to complimentary mechanics between the two sailors in paired testing providing a greater advantage in the in-line system. There was also some evidence that the conventional system is better at lower loads, as exhibited by a performance benefit for the secondary grinders (2.0%, $p = 0.017$). Although results varied across the testing conditions, the large performance benefit observed for the in-line system in paired grinding suggests that this orientation may be advantageous in terms of grinding performance.

INTRODUCTION

On-water performance in the America's Cup sailing competition is determined by a number of factors including tactics, crew work and boat design. Of these factors the design of an America's Cup yacht is arguably the most crucial for success and as such syndicates will spend millions of dollars on the research, design, and testing of their vessels trying to balance raw speed, durability, and functionality for crew performance while staying within the design laws of the competition. One aspect of interest for designers is the deck layout and in particular the placement and orientation of the grinding pedestals.

Grinding is the manual hand cranking of winches attached to the sail lines responsible for the movement of the sails, a task which therefore provides the power behind tacking and gybing and influences boat speed [18]. Performed in a standing position, the set-up of the winch system means that sailors are required to grind forward – pushing away from their body at the top of the rotation; and backward – pulling towards their body at the top of the rotation. Neville, Calefato et al. [19] observed that more accomplished America's Cup teams completed manoeuvres (of which grinding is a crucial component) faster than the less well performed crews. Because of this observed relationship between grinding and performance it is important to know what effect any re-configuration of deck layout is likely to have on the physical grinding performance of the sailors. Pedestal orientation may have an influence on grinding due to the effect of heel – the sideways lean of the yachts' deck when sailing up-wind, which can be over 30° in strong wind. In the campaign for the 2007 America's Cup, the Emirates Team New Zealand syndicate were interested in identifying any differences in grinding performance between two orientations for the primary grinding pedestals which predominantly control the headsail/jib during up-wind sailing. The two pedestal orientations (see Figure 1) were the "conventional" system where the primary pedestals were orientated fore-aft (resulting in left-right/bi-directional lateral tilt when grinding under heel conditions), and an alternative "in-line" system where the pedestals were orientated across the boat (downhill-uphill/anterior-posterior tilt when grinding under heel).

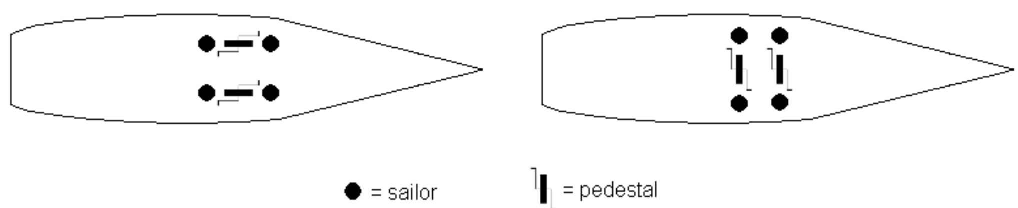


Figure 4: Schematic representations of the conventional (left) and in-line (right) orientations for the primary grinding pedestals as viewed from above.

There is little published research on America's Cup grinding, although there are a number of papers on the kinematically similar seated arm cranking exercise which is often used in rehabilitation of shoulder injury and wheelchair users [20]. Performance in grinding or arm cranking has been shown to be influenced by conditions such as grinding direction [20-22] and system resistance [22-23], but no published studies have quantified the effect of deck heel/tilt. The in-line pedestal system had been used previously by the One World syndicate in their 2003 America's Cup campaign. Unofficial reports from the One World syndicate's grinding performance testing indicated that the in-line system was favoured under all handle speeds and load conditions, particularly when the load was heavier [24]. However, due to the confidentiality issues associated with America's Cup campaigns, Emirates Team New Zealand did not have access to actual data or testing specifics from the One World testing to confirm these findings. The combination of this ambiguity and the possibility of individual response variation between sailors to such perturbations meant there was still a requirement to determine the size and direction of any effect of different pedestal orientations on grinding performance. It was also not able to be confirmed whether the One World testing was performed using forward or backward grinding, a matter of some importance due to the previously documented influence of direction on performance [22], technique [21, 25], and muscular activation [20].

The majority of on-water grinding work is performed by the “principal” grinders, consisting of both the primary and mainsheet grinders; sailors who, due primarily to their muscular strength, are particularly well suited to the physical demands of grinding. During sailing manoeuvres however, it is common practice for the principal grinders to be assisted by a “secondary” grinder – another sailor who specialises in a different on-board role but contributes to the grinding task where possible. Paired grinding is therefore a common occurrence during racing and should be evaluated as the influence of deck heel may differ with the coupling of synergetic forward and backward grinding mechanics, which have been found to differ [25].

The purpose of this study was therefore to quantify the effect of grinding pedestal tilt orientations on forward and backward grinding performance for individual and paired grinders.

METHODS

Two classifications of deck heel testing were performed: individual and paired. Both used the same testing protocols but were performed on separate days. The one difference in the paired testing being the two sailors grinding together (one grinding forward, one grinding backward) from opposite sides of the pedestal, in contrast to the single sailor, single direction individual condition.

Participants

Twelve male America’s Cup sailors who performed grinding routinely as part of their on-board sailing role participated in this study. Characteristics are presented in Table 1. Sailors were categorised by sailing role and physical capability as either ”principal” (n = 4) or ”secondary” (n = 8) grinders. All procedures used in this study complied with the guidelines of the Auckland University of Technology Ethics Committee.

Table 4: Characteristics (mean ±SD) for sailors collectively and by group.

	Principal (n = 4)	**Secondary (n = 8)**	***All (n = 12)***
Age (years)	30.8 ±1.9	35.3 ±7.0	33.7 ±6.0
Height (cm)	190.8 ±7.6	182.5 ±4.4	185.3 ±6.7
Mass (kg)	109.6 ±9.9	88.4 ±9.1	95.5 ±13.8

Equipment

In order to evaluate the influence of grinding pedestal orientation in heeled conditions on grinding performance a custom-built instrumented tilt-able grinding ergometer (Dynapack, Wellington, New Zealand) was constructed which allowed the manipulation of deck heel and system resistance (load) in a controlled manner. The grinding ergometer had standard pedestal (870 mm vertical) and crank arm (250 mm) dimensions for a main sheet grinding pedestal on an America's Cup class yacht (see Figure 2). Gearing for the ergometer was linked through a multiple-speed dynamometer set up to output a number of grinding performance measures. Power output was obtained from the grinding ergometer using a bi-directional oil hydraulic system custom designed to meet the tactile characteristics of on-water grinding. Speed was based on a 24-slot disc attached directly to the motor input shaft. Output was obtained via an analogue to digital converter using 8-bit resolution to a C++ customised data collection system sampling at 40 Hz. Mechanical load was varied using a custom designed cog selector allowing 1:1 and 3:1 ratios driven by toothed belts. Hydraulic load was applied using a dynamic closed loop controller modified to operate at low speed. Calibration was performed using calibrated masses and known lever lengths, and the machine was verified as accurate to 0.5% or better throughout its range. A motorised hydraulic strut enabled the grinding ergometer base to be tilted bi-directionally up to 30°, allowing the simulation of deck heel in either the sagittal or frontal planes relative to the orientation of the grinding pedestal. For test conditions a 25° heel angle was chosen (see Figure 2) because it represents the higher end of deck heel experienced and should be steep enough to show differences between the different configurations. While in some conditions deck heel does get steeper (30°+), this is uncommon and there is relatively little grinding work performed at these maximum heel angles.

Figure 5: Images of the grinding ergometer positioned flat (left) and at 25° anterior-posterior tilt (right).

Procedures

Two testing sessions were performed for each of the individual and paired classifications. Both sessions were completed on the same day, at least two hours apart, and consisted of a single trial of all ten heel and directional conditions. In the first session, condition order was randomised to reduce order effects, with trials alternating between forward and backward grinding to reduce the influence of acute muscular fatigue. In the second session, conditions were presented in a reverse-randomised order based on the first session in order to correct for any chronic fatigue build-up that may have occurred across the duration of a session. Prior to each testing session, the sailors completed a self-determined warm-up on the grinding ergometer prior to testing. All grinding trials were maximal effort, eight-seconds in length, and separated by a minimum three minute rest period. Verbal “go” and “stop” signals were the only in-trial feedback.

In each session both forward and backward grinding performances were tested in five heel conditions:

Flat: 0° (control).

Above: Grinding from above the pedestal with 25° deck heel.

Below: Grinding from below the pedestal with 25° deck heel.

Right: Grinding with right-hand side of the body on the high-side of the pedestal with 25° deck heel.

Left: Grinding with left-hand side of the body on the high-side of the pedestal with 25° deck heel.

By averaging performance from all the individual component conditions contributing to a system we were able to ascertain the system’s influence on overall performance. The conventional (lateral tilt) system was composed of the “Right hand high” (forward and backward) and “Left hand high” (forward and backward) conditions, while the in-line (anterior-posterior tilt) system was made up of the “Above” and “Below” conditions (forward and backward). A no tilt control/reference system was also included using the flat forward and backward conditions.

All ten conditions were performed against a constant load of 48 N m for individual secondary grinders, 68 N m for individual principal grinders, and 100 N m for paired testing. Anecdotal evidence from the previous testing by One World showed that heavier loads were more likely to elicit performance differences between heel directions [24] and as such, testing should be conducted towards the upper end of a sailor’s physical capability. Loads were therefore selected to produce an average handle speed for each group of approximately 100 rpm, indicative of a heavy relative resistance. The 25° angle was selected as an upper range heel angle experienced in racing conditions, and angles for the ergometer platform were verified using a SmartTool™ digital spirit level (M-D Building Products, Oklahoma, USA).

For paired testing, six sailor pairings were created to cover all likely pairing permutations during racing. Pairings were set prior to testing and the same two sailors remained in a pair throughout all conditions.

2 x Principal + Secondary grinder pairings

1 x Principal + Principal grinder pairing

3 x Secondary + Secondary grinder pairings

Given feedback from the sailors, one alteration was made to the equipment set-up between the individual and paired testing with some additional non-skid surfacing added to the deck of the grinding ergometer.

Data and statistical analyses

A number of potential variables of interest were available from the grinding ergometer; however, external work (kJ) over a set time presented the most face validity as a performance measure since it corresponds functionally to the total amount of sail line able to be pulled in during that time period. Additionally, external work over five seconds has been previously shown to be a more reliable measure than peak power [22]. As a result the performance measure of interest for this study was external work (kJ). Raw power values were calculated by the Dynapack ergometer software using the formula: Power (W) = Torque x (2π*rpm)/60. The raw power curve was then smoothed using a second order recursive band-pass filter (low cut-off = 2 Hz, high cut-off = 12Hz), and external work calculated using a customised Labview (National Instruments, Texas) program. External work performed is the five-second integral of the area under the power curve, starting at the occurrence of peak power.

Descriptive statistics for all variables are represented as mean and standard deviations (spread of results among participants). Magnitude of differences in performance between conditions are presented as percentages and Cohen effect sizes with associated confidence limits, calculated from log-transformed data using the spreadsheet of Hopkins [26]. The presence of significant systematic discrepancy between reliability measures of different grinding conditions was determined using a two-tailed unpaired *t*-test with alpha set at $p<0.05$. Coefficient of variation (CV) was calculated to examine relative variability between tilt conditions.

RESULTS

Individual conditions

For combined group data the order of performance (best to worst) for forward grinding in the five conditions was: Below, Flat, Right hand high, Above and Left hand high. Performance order for the backward grinding conditions was: Flat, Left hand high, Below, Right hand high and Above.

Greater external work (see Table 5) was performed in all forward grinding conditions in comparison to the backward, with the best backward condition (flat) still significantly lower in external work performed (-5.5%, $p = 0.029$) than the worst forward condition (Left hand high). The average reduction in output when grinding backwards was 13.6%, with the strongest forward position (Below) producing as much as 25.5% greater work ($p < 0.001$) than the weakest backward condition (Above).

Table 5: Mean (± SD) grinding performance (work, kJ) for all sailors during individual heel conditions. Difference in the mean (M_{diff}%) relative to the flat baseline condition (0°) and Cohen effect sizes are presented with associated 90% confidence limits (90% CL) and *p*-values.

Tilt condition	**Work (kJ)** Mean ± SD	**M_{diff}%** (90% CL)	**Effect size** (90% CL)	***p***
Forward				
0° – Flat	90.7 ± 35.2	--	--	--
25° – Left	85.4 ± 31.3	-5.0 (-8.2, -1.7)	-0.12 (-0.20, -0.04)	0.024
25° – Above	87.3 ± 31.2	-2.7 (-6.4, 1.2)	-0.06 (-0.15, 0.03)	0.227
25° – Right	88.1 ± 33.0	-2.2 (-6.1, 1.9)	-0.05 (-0.14, 0.04)	0.337
25° – Below	92.2 ± 36.8	1.2 (-1.0, 3.4)	0.03 (-0.02, 0.08)	0.337
Backward				
0° – Flat	80.8 ± 30.7	--	--	--
25° – Above	68.6 ± 22.4	-13.4 (-17.8, -8.7)	-0.33 (-0.45, -0.21)	0.0009
25° – Right	75.2 ± 25.0	-5.3 (-9.7, -0.6)	-0.12 (-0.24, -0.01)	0.070
25° – Below	79.5 ± 30.1	-1.6 (-3.6, 0.5)	-0.04 (-0.09, 0.01)	0.193
25° – Left	79.3 ± 27.5	-0.7 (-3.7, 2.4)	-0.02 (-0.09, 0.05)	0.675

Above = standing above pedestal; Below = standing below pedestal; Right = right side of the body on the high-side of pedestal; Left = left side of the body on the high-side of pedestal.

Table 6: Mean (± SD) grinding performance (work, kJ) grouped for all sailors to compare between conventional and in-line systems in individual and paired testing. Difference in the mean (M_{diff}%) relative to the flat baseline condition (0°) and Cohen effect sizes are presented with associated 90% confidence limits (90% CL) and *p*-values.

	Work (kJ) Mean ± SD	**M_{diff}%** (90% CL)	**Effect size** (90% CL)	***p***
Individual				
Flat	85.7 ± 32.9	--	--	--
In-line	81.9 ± 29.9	-3.9 (-5.4, -2.3)	-0.09 (-0.13, -0.05)	0.002
Conventional	82.0 ± 28.8	-3.3 (-5.5, -1.0)	-0.08 (-0.13, -0.02)	0.028
Paired				
Flat	183.0 ± 16.2	--	--	--
In-line	173.8 ± 13.6	-4.9 (-6.2, -3.7)	-0.49 (-0.62, -0.36)	0.0006
Conventional	159.9 ± 16.2	-12.7 (-14.7, -10.7)	-1.33 (-1.55, -1.10)	0.0001

Comparing systems

During the individual testing both the in-line and conventional systems resulted in significantly reduced performance, with 3-4% less work performed than in flat grinding (see Table 6). There was no significant difference in performance between the two systems, with the conventional system showing only 0.6% ($p = 0.355$) greater power output. In paired testing, the in-line system resulted in a similar 4.9% decrement in performance; however the conventional system reduced performance by 12.7% relative to the flat condition – significantly lower than both the flat ($p = 0.0001$) and in-line ($p = 0.002$) systems.

Performance by on-board role

Results from individual testing are shown in Table 7, grouped by system and with the sailors classified as either principal or secondary grinders. Principal grinders performed significantly worse (~6%) in both the heel systems compared to flat, with a small, non-significant difference (1.0%, $p = 0.254$), positive in the direction of the in-line system. The negative performance impact from the heel conditions was considerably less for the secondary grinders. In particular, the difference in performance between flat and conventional system grinding was negligible (0.6%), with the conventional system significantly out-performing the in-line system (2.0%, $p = 0.017$).

Table 7: Mean (± SD) grinding performance (work, kJ) for sailors grouped by on-board role to compare between conventional and in-line systems in individual testing. Difference in the mean (M_{diff}%) relative to the flat baseline condition (0°) and Cohen effect sizes are presented with associated 90% confidence limits (90% CL) and *p*-values.

	Work (kJ) Mean ± SD	**M_{diff}%** (90% CL)	**Effect size** (90% CL)	***p***
Principal				
Flat	119.9 ± 13.4	--	--	--
In-line	113.1 ± 11.7	-5.6 (-8.5, -2.6)	-0.34 (-0.52, -0.15)	0.023
Conventional	112.0 ± 11.8	-6.5 (-9.0, -4.0)	-0.40 (-0.55, -0.24)	0.010
Secondary				
Flat	58.4 ± 5.4	--	--	--
In-line	56.9 ± 4.6	-2.5 (-3.9, -1.1)	-0.22 (-0.33, -0.10)	0.018
Conventional	58.0 ± 4.8	-0.6 (-1.9, 0.8)	-0.05 (-0.17, 0.07)	0.445

DISCUSSION

A limitation of this study was the inability to collect any additional quantitative data on the sailors grinding technique relative to the heel condition presented. This discussion will therefore focus on the measured performance results, while making some subjective qualitative assessment of possible mechanisms of change based on researcher and sailor observations.

Individual conditions

Grinding forward from below was notable as the only heel condition to out-perform the flat reference condition, albeit by a relatively small, non-significant margin. A possible reason for this is that the likely negative influence of a less stable base of support from being on a slope is counteracted by a more balanced trunk position. The tendency in forward grinding is for the feet to be positioned behind the body which then leans in to and over the pedestal (see Figure 6, from another study). This body position below the pedestal creates a more upright alignment of the trunk to the grinding handles, which may benefit application of force throughout the entire range of motion. A similar effect may also be present in backward grinding from below, which only showed a small loss in performance relative to flat, except that the benefits of better trunk alignment are likely to have been moderated by the different mechanics involved in backward grinding – feet closer to the pedestal and pulling away. Assuming the theories proposed here regarding trunk alignment and balance are correct this would also go some way to explaining the relatively poor performance in both the “above” conditions, although probably not the entirety of the decrement seen in the backwards below condition. It would seem that the foot position in backward grinding (forward of the centre of mass), in conjunction with a surface sloping down anteriorly and a predominantly pull-based upper body action, makes for a particularly unstable base of support with a predisposition for slippage in the anterior direction. In addition, it has previously been shown that the horizontal distance of the centre of mass from the axis of rotation of the handles has a positive relationship with backward grinding performance [27], a factor which is considerably disadvantaged by the above pedestal positioning.

Figure 6: Examples of body position during forward (left) and backward (right) grinding with no deck heel.

In comparison with the anterior-posterior heel conditions associated with the in-line system, the technique perturbations from lateral heel conditions from the conventional system would seem relatively straight-forward. While the lateral tilt would be expected to similarly decrease performance (relative to flat conditions) by de-stabilising the base of support, the influence on overall body position and grinding biomechanics would appear to be relatively minimal and uniform between the two lateral tilt directions. There appeared to be a substantial bias between the two lateral heel conditions in both forward and backward grinding. The most likely explanation appears to be the influence of dominance, as the majority of the sailors in this study considered themselves right-hand dominant. In lateral heel conditions it seems to be beneficial to have the dominant hand on the windward (uphill) side of the grinding pedestal and more advantageous to have the dominant hand on the leeward (downhill) side during backward grinding.

Averaged across all grinding conditions both the conventional and in-line heel systems showed significantly less output (3-4%) than grinding on the flat, however there was only a negligible 0.6% performance difference between the two systems, with the conventional system marginally better. This similarity in overall performance occurred because of the relative balance between different conditions. For instance, on the in-line system while the sailors tested were very strong grinding forwards from below, their performance was significantly compromised when grinding backwards from above. A similar balance can be observed between the apparent dominant/non-dominant hand biases observed in the conventional system. These findings are in contrast to the One World testing, which reportedly found the in-line system to perform better than the conventional system under all load conditions and handle speeds [24], something which was not apparent from our testing. In the One World testing the heavier loads were favoured more for the in-line system [24] which was somewhat consistent with the results from our study.

The sailors in our study were separated into “principal” and “secondary” grinder groups with different loads catered to their relative physical capabilities. When analysing these groups separately sailors in the principal group (higher resistance) showed no significant difference in performance between systems while sailors in the secondary group performed better (2.0%) using the conventional system. Therefore, while not conclusive, the data obtained may indicate a cross over in the performance of the two systems not seen in the One World testing, with the conventional system better at lower loads and the in-line system more advantageous under higher loads. Alternatively it may be an indication of the physical characteristics of the sailors in each group, whereby the sailors in the principal group who are typically taller, heavier and stronger than those in the secondary group, are better suited to cope with or benefit from the technical perturbations caused by the in-line pedestal system.

Paired testing

Paired testing was included to provide an additional examination of any performance effects from the two pedestal orientations. There was a marked difference in the relative performance of the two systems compared to the relatively even individual testing, with the in-line system out-performing the conventional system by 8% (p<0.001) in paired testing. These differences are in the order of those reported from the One World testing.

So the question is why there is such a discrepancy in the comparative results for the two systems between the individual and paired testing? One potential explanation lies in the way in which force is applied to the grinding handles throughout a revolution. In solo grinding there are noticeable “dead-spots”, or low torque sectors in the 360° cycle, as illustrated by data from a separate study shown in Figure 7 [25]. Because of the difference in the shape of the torque curves for forward and backward grinding the dead-spots tend to be smoothed out in paired grinding. It may be that the relative amount of “dead-spot smoothing” is greater in an in-line set up compared to the conventional system, resulting in a more efficient grinding cycle with less variation in handle speed and greater performance. This hypothesis of a smoother, more efficient cycle is supported by lower overall performance variability (across all pairings) in the paired in-line system (CV = 7.8%) compared to either the flat (CV = 8.9%) or conventional (CV = 10.1%) systems.

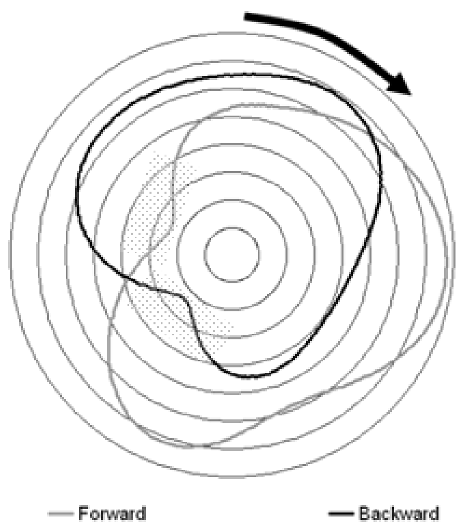


Figure 7: Examples of typical torque curves for forward (grey) and backward (black) grinding in flat conditions. Torque increases as the traces move away from the centre. Arrow indicates the direction of handle rotation. Hatched areas indicate torque “dead spots”.

A second possibility for the relatively better performance of the in-line system in the paired testing is linked to the additional non-skid surfacing added to the deck of the grinding ergometer following the completion of the individual testing. While testing conditions were the same for all heel variations in the paired testing, it may be that the added grip was more advantageous for the in-line system conditions. In particular, backward grinding from above, which was particularly poor in the single person trials, appears most likely to have benefitted from this change given the previously identified traction issues, although this was not able to be quantitatively assessed. While the change in experimental set-up between the individual and paired results is not ideal, it should be noted that the non-skid surfacing was added for the paired testing to create a closer match between the deck characteristics of the grinding ergometer and those present on the yacht. Results from the paired testing, and consequently the performance benefits of the in-line system observed in this testing, should therefore be considered to have greater validity than the individual testing results with respect to on-water/competition conditions.

CONCLUSIONS

There are numerous factors that are likely to influence the primary pedestal system that an America's Cup syndicate chooses, of which grinding performance when the boat is heeled is one. This study has shown that grinding performance does vary with different heel directions, but that results were affected by: (a) direction of grinding, (b) grinding experience/role, and (c) individual versus paired grinding. In individual (single sailor) trials there was no overall difference between the conventional (lateral tilt) and in-line (anterior-posterior tilt) systems; however, when sailors were separated by on-board role/grinding ability there was a small benefit (2%) of the conventional system for the secondary (less accomplished) grinders. In paired grinding however, there was a significant overall performance benefit (8%) observed for the in-line system. While there are numerous design factors involved in choosing pedestal orientation on an America's Cup yacht, it appears that the in-line system may be the preferred system from a pure grinding performance point of view.

CHAPTER 4

AMERICA'S CUP SAILING: EFFECT OF GRINDING DIRECTION ON EMG, KINEMATICS, AND TORQUE APPLICATION

This chapter comprises the following paper that has been submitted to *Journal of Sports Sciences*:

Pearson SN, Hume PA, Cronin JB, Slyfield D. America's Cup Sailing: Effect of grinding direction on EMG, kinematics, and torque application. Journal of Sports Sciences. 2009; submitted, November.

(Author contribution percentages: SP: 83%, PH: 10%, JC: 5%, DS: 2%).

OVERVIEW

Grinding is a key physical element in America's Cup sailing. This study aimed to improve understanding of grinding performance by examining kinematics and muscle activation patterns in relation to torque applied in forward and backward grinding. Ten male America's Cup sailors (33.6 ±5.7 years, 97.9 ±13.4 kg, 186.6 ±7.4 cm) participated. In forward grinding peak torque (77 N m) occurred at 95° (0° = grinding crank vertically up) on the downward section of the rotation at the end of shoulder flexion and elbow extension. Backward grinding torque peaked at 35° (69 N m) following the pull action (shoulder extension, elbow flexion) across the top of the rotation. During forward grinding, relatively high levels of torque (>50 N m) were maintained though the majority (72%) of the cycle, compared to 47% for backward grinding, with sections of low torque corresponding with low numbers of active muscles. Variation in torque was negatively associated with forward grinding performance (r = -0.60; 90% CI -0.88 to -0.02) but positively associated with backward performance (r = 0.48; CI = -0.15 to 0.83). Overall, mechanics of grinding differed considerably according to direction and presents an argument for divergent training methods to improve forward and backward grinding performance.

INTRODUCTION

The America's Cup in generally regarded as the most prestigious competition in sailing and is the oldest active trophy in international sport, dating back to 1851 [28]. On-water performance in America's Cup competition is determined by numerous factors including tactics, crew work and yacht design, however, in terms of physical human performance during racing, grinding is considered to be the primary physical activity [1].

Grinding is a cyclic upper body task requiring the manual arm cranking of winches which control the movement of the mast and sails, making it a crucial component of manoeuvres such as tacking (turning on an upwind leg) and gybing (turning on a downwind) [18]. Grinding is performed in a standing position and the set-up of the winch system means that sailors are required to perform grinding in both a forward direction – pushing away from their body at the top of the rotation; and backward – pulling towards their body at the top of the rotation. In race analysis of the 32nd America's Cup and associated Louis Vuitton Challenger series, Neville, Calefato et al. [19] reported that an average of 20 tacks (5.5 ±0.5 s) and 8 gybes (11.2 ±1.4 s) were performed during a race. These values were lower than previously reported figures of 30 tacks and 15 gybes per race [29]. However, it was calculated that when combined with mark roundings and the more frequent but less demanding grinding activity of sail trimming, a sailor whose principle role was grinding could expect a work to rest ratio of ~1:6 over an average 82 min race, and up to 1:3 in close racing. More accomplished teams (top four of the 11 challengers) completed manoeuvres in significantly shorter time than the less well performed crews [19], a finding that highlights the important relationship between grinding capability and overall race performance.

In addition to the performance aspects, grinders have been identified in a number of epidemiological studies as having the highest rate of injury amongst America's Cup crew members [30-33]. Although these studies reported sometimes conflicting findings (possibly due to different methodologies), soft tissue injuries to the upper limb made up a large proportion of the preventable (non-accident/impact) injuries suffered by grinders, with the grinding activity itself directly attributed to 30% of injuries in this group [34]. As such, a better understanding of the muscles, movements, and loading patterns utilised during grinding may provide useful information for the preventative conditioning of sailors who perform grinding as part of their on-board role.

In recent years there has been an increasing body of research focussed on America's Cup sailing from sport science and medicine perspectives. With regards to the grinding activity in particular, studies examining the physiological [1, 29] and strength and power [35] factors associated with performance, along with descriptions of the physical characteristics [4, 19], nutritional requirements [36], and competition demands [19, 37] have all been published in the last few years. Currently no one has examined the biomechanical motion of sailors performing the grinding activity, although there have been papers in this area on the kinematically similar seated arm cranking exercise, which is often used in rehabilitation and for wheelchair users [20]. Arm cranking papers have reported that hand-grip/forearm orientation affects muscle activation patterns [38], that shoulder height relative to the crank axis has varying effects on performance[39-40], and that backward arm cranking is less proficient than forward, based on reduced kinematic variability at the elbow [21]. Possibly of most relevance, Bressel [20], in a comparison of forward and reverse (backward) arm cranking, observed little difference in either upper limb kinematics or oxygen consumption, but found that backward arm cranking required significantly greater activity of the biceps brachii, deltoid, and infraspinatus muscles. While there may be some cross-over from the findings of this body of research, the differences in body position and posture due to the standing position adopted during America's Cup grinding mean that there is justification in examining the mechanics of this activity in it's own right. Therefore, the purpose of this study was to describe the kinetic, kinematic, and muscular activation characteristics of the forward and backward grinding movements in America's Cup sailing.

METHODS

Participants

Ten male America's Cup sailors (33.6 ±5.7 years, 97.9 ±13.4 kg, 186.6 ±7.4 cm) participated in this study. While the sailors varied in their primary role within the team, all performed grinding regularly as part of their on-board role. As maximal strength has previously been shown to be a key predictor of grinding performance [35] predicted one-repetition maximum (1RM) scores for the bench press (146.2 ±30.1 kg) and bench pull (122.3 ±18.8 kg) resistance strength training exercises were calculated using the methods of Mayhew [41] as an additional classification variable.

All procedures used in this study complied with the guidelines of the AUT University Ethics Committee and had been granted ethical approval (reference 04/221).

Procedures: Performance testing

Grinding performance testing was conducted on a custom-built grinding ergometer (Dynapack, New Zealand) capable of applying variable resistance, for which the technical specifics and reliability have previously been reported [22]. The ergometer was set up with standard pedestal (87 cm vertical) and crank arm (25 cm) dimensions for a main sheet grinding pedestal on an America's Cup class yacht (see Figure 8). Testing was conducted in a manner familiar to the sailors, as the protocol was used regularly for grinding performance testing as part of their fitness monitoring. Performance was assessed in four conditions: forward and backward grinding and against a moderate (48 N m) and heavy (68 N m) resistance. Following a self-determined warm-up on the grinding ergometer the sailors performed two maximal-effort grinds for each condition (eight in total), of eight-seconds duration and separated by a rest period of at least two minutes.

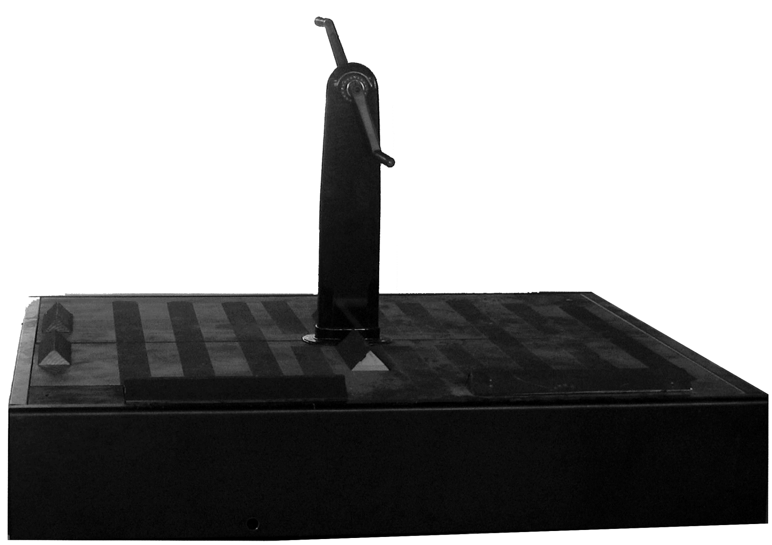


Figure 8: Ergometer for grinding performance testing.

For the grinding performance measure raw power values were calculated by the Dynapack ergometer software using the formula: Power (W) = Torque x (2π*rpm)/60. Raw power curves were smoothed using a second order recursive Butterworth low pass filter with a cut-off frequency of 6 Hz. Peak power and external work were calculated using a customised Labview (National Instruments, Texas) analysis program. Total work (J) performed during the five-second period from peak power was determined for each trial, and the two-trial mean calculated. External work was used as the performance measure as this variable has been shown to be more reliable than peak power [22].

Procedures: Motion analysis

Grinding for the motion analysis section of this study was conducted independently (within four weeks) of the grinding performance testing, although the protocol used was very similar. The primary point of difference was that the ergometer resistance was not set at an absolute level; rather, tests were performed at relative loads customised to the individual sailor so that all participants were grinding within a similar speed range when grinding maximally (90-120 rpm), which incorporated the typically observed drop-off of 20-30 rpm during an eight-second trial. The decision to use relative loads was made due to the reasonably wide range of grinding abilities represented in the sample of interest to this study. As this section of study was focussed on the mechanics of the movement rather than direct performance comparisons the desire was to examine grinding performance at high load (which has the biggest influence on boat performance) without inducing the degradation in basic technique that can be observed when an individual is performing at an excessively high load relative to their capability. If a set load was used for all participants, individuals either performing at loads much too easy or much too hard for their ability would likely have confounded the description of the grinding movement. As such, all individuals performed two maximal effort grinds in each of the forward and backward direction (four in total), against a moderate-heavy resistance, scaled relative to capability.

During the performance of grinding during the motion analysis session, biomechanical data were captured and averaged over five complete revolutions during the middle of the eight-second trial, avoiding the initial start/acceleration phase. Data were collected on muscle activation patterns using electromyography (EMG), torque application throughout a revolution, and sagittal plane kinematics.

EMG signals were collected using a Bortec AMT-8 system (Bortec, Canada) with pre-gelled Ag/AgCl surface electrodes. A band pass Butterworth filter (10-500 Hz) was applied to all signals, which were then sampled at 1000 Hz. Six upper body muscle sites were used: posterior deltoid, latissimus dorsi, triceps brachii (lateral head), anterior deltoid, pectoralis major (sternocostal head), and biceps brachii. Electrodes were placed according to the guidelines of Basmajian and Blumenstein [42] and the wires connected to the electrodes were well secured with tape to avoid movement artefacts. EMG data were full-wave rectified and low-pass filtered (15 Hz cut-off frequency, based on visual observation of the linear envelopes). The signal from each muscle was normalised to a 100% scale of its own activation throughout the five-revolution analysis period, with 0% as the lowest recorded signal and 100% as the highest recorded signal. Periods of muscle activity and inactivity were identified from prominent bursts of activity using visual determination which has been suggested to be potentially more desirable than using automated absolute thresholds [43-44] and has also been used previously in comparable research on muscle activation in seated arm cranking [20].

Torque application and angular position data were collected from the grinding handles using an adapted SRM (Schoberer Rad Messtechnik) Powermeter system with torque analysis module (SRM, Germany) and a sampling frequency of 200 Hz. The characteristics of the captured torque-angle data output from the SRM system were such that averaging of the five cycles of interest was conducted without any additional smoothing.

Full body sagittal plane motion was recorded using a video camcorder (Sony DCR-TRV120E) placed at 10 m from the ergometer, perpendicular to the direction of sagittal motion and recording at 50 frames/s with a 1/500 shutter speed. To aid digitisation, markers were placed on the distal head of the fifth metatarsal bone, lateral malleolus of the ankle, lateral condyle of the tibia, greater trochanter, lateral aspect of the acromion process, lateral epicondyle of the humerus, and the styloid process of the ulna. Two-dimensional sagittal plane relative joint angles in degrees (°) were obtained through digitisation using APAS (Ariel Dynamics, USA) for the ankle, knee, hip, shoulder, and elbow. Shoulder angle was measured using the trunk as a relative 0° position, with a positive value moving anteriorly into flexion. Trunk angle was measured relative to vertical, with a positive value indicating the shoulder was anterior to the hip. Kinematic data were summarised using four reference points during the grinding cycle based on handle position: 0° = handle vertically above the point of rotation (hub); 90° = horizontal to the hub, moving from 0° in the direction of rotation (on the sailor's side of the pedestal for forward grinding, away from the sailor for backward); 180° = vertically below the hub; 270° = horizontal to the hub, on the way back up towards the 0° position.

Data were synchronised using the onset of a five-volt pulse to the computer-based data acquisition system, generated simultaneously with the activation of an LED light in the line of view of the video camera.

Statistical analyses

Descriptive statistics for all variables are represented as mean and standard deviation (SD). The presence of significant systematic discrepancy between variables was determined using a two-tailed unpaired *t*-test with alpha set at $p<0.05$. In addition to descriptive data the relationship between variability in torque application throughout a revolution and grinding performance was also examined using Pearson correlation analysis. Grinding performance (J) for an individual was log transformed and corrected for maximal strength (1RM – also log transformed), with the residuals from this correction plotted against the sailor's variation in torque application, as represented by the standard deviation of the log-transformed SRM data. To make inferences about true (population) values of the relationship, the uncertainty in the effect was expressed as likelihoods that the true value of the effect represents substantial change (harm or benefit) using the methods of Hopkins [45], with the smallest worthwhile change set as 0.10 standardised Cohen units [46] and confidence limits set at 90%.

RESULTS

Torque application

Greatest torque application occurred through 60-200° for forward grinding and 300-40° for backward grinding (see Figure 9). Group average peak torque was 77 N m at 95° for forward grinding and 69 N m at 35° for backward grinding. Variation in torque application throughout the grinding cycle was negatively associated with forward grinding performance ($r = -0.60$; 90% CI -0.88 to -0.02) but positively associated with backward performance ($r = 0.48$; CI = -0.15 to 0.83).

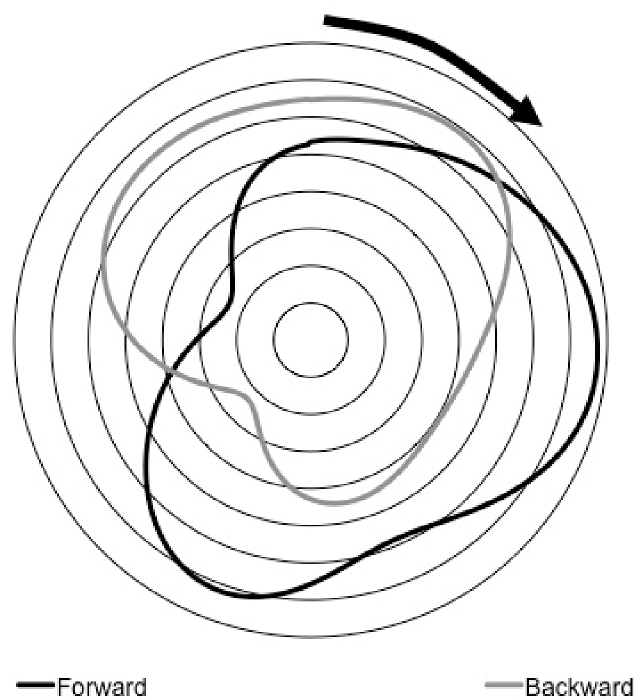


Figure 9: Average torque-angle curves for forward (black) and backward (grey) grinding. Torque increases as the traces move away from the centre (lines = 10 N m increments). Arrow indicates the direction of handle rotation. 0° = crank handle vertically upwards from the centre.

Joint kinematics

Data from the kinematic analyses are presented in Table 8, and examples of body position during backward and forward grinding are shown in Figure 10. When grinding forward the sailors typically stood more upright and leaned over the grinding pedestal when compared to backward grinding, as indicated by significantly less hip flexion and more forward trunk lean throughout the cycle. Sailors also tended to have a more plantar flexed ankle and greater knee flexion during backward grinding. Elbow and shoulder angles differed significantly at 90° and 270° but tended to be more similar at 0° and 180°.

Table 8: Average (±SD) joint angles for forward (Fwd) and backward (Back) grinding presented at four positions (in degrees) during the cycle. Position (°) increases in the direction of motion.

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 ($p<0.05$)

Figure 10: Examples of forward (left) and backward (right) body position at 0° crank angle.

Muscle activation

EMG activity patterns for forward and backward grinding are presented in Figure 11, with muscles paired according to approximate agonist-antagonist relationships based on typical involvement in joint actions.

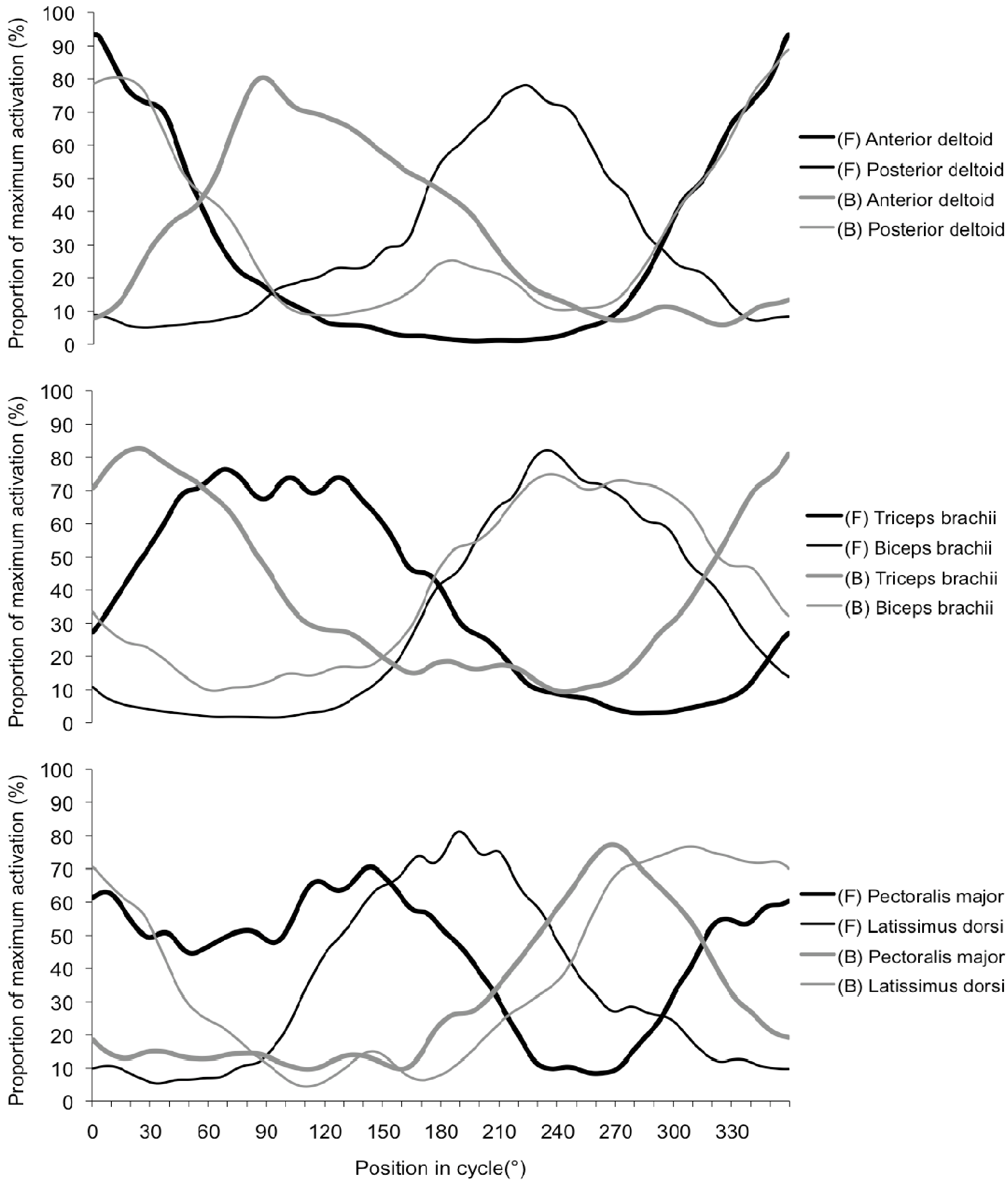


Figure 11: Average EMG activity patterns during forward (F) and backward (B) grinding for 10 grinders. Crank angle defined as 0° when positioned vertical and above the pedestal. Crank angles are positive in the direction of motion.

DISCUSSION

One of the most novel features of this study was the examination of the way in which torque was applied throughout the rotation. While similar research has been performed previously with the lower limb in cycling [47-49], to the authors knowledge this is the first study to produce torque-angle curves for upper limb arm-cranking – either in a standing position (as in America's Cup grinding) or seated.

Cycling literature has consistently reported that torque or applied force for a single limb occurs almost entirely in the down stroke (0-180°, with 0° crank position again vertically upward) with virtually no positive force, and in many cases a negative force applied during the following up stroke [48-50]. In contrast torque during grinding was never negative, with the mean curve remaining above 20 N m throughout the entire 360° cycle. What was also notable was the way in which torque application differed between forward and backward grinding. While backward grinding could be said to follow a similar pattern to cycling in which the majority of torque was applied through half of the rotation (270-80°) with a considerable drop-off through the remaining half-circle, in forward grinding a high level of force at the handles was maintained through a much greater proportion of the rotation (340-240°), leaving only a relatively small "dead spot" of ~100° in which torque was reduced. This again is in contrast to the cycling literature, with Neptune, Kautz & Zajac [50] observing very little difference in tangential pedal force between forward and backward pedalling.

Relative levels of torque throughout the rotation were also reflected in muscle activation patterns. On an individual basis muscle activation patterns were consistent with the bi-phasic nature of grinding with distinct periods of activation and in-activation, which has also been seen previously in seated arm cranking [20], however, the spread of muscles active at any one time differed notably with grinding direction. In backward grinding there was a high level of activation from five of the six muscles monitored (anterior deltoid being the only exception) during the upper half of the rotation (240-80°) where torque rose rapidly and peaked before declining again as the crank arm came in close to the sailors body at ~90°. Through the lower half of the cycle however, as the crank arm passed down to its lowest point (180°) and then started moving upward on the side of the pedestal away from the sailor the only notable activity was from smaller muscles – anterior deltoid and biceps brachii. At the point of minimum backward grinding torque (227°, 23 N m), biceps brachii was the only muscle showing any meaningful level of activation, with pectoralis major and latissimus dorsi just beginning to fire. Conversely, forward grinding showed a much more even spread of muscle activity throughout the rotation, with anterior deltoid, pectoralis major and triceps brachii dominant through the top and downward sections (310-150°) and latissimus dorsi, posterior deltoid and biceps brachii highly active through the majority of the bottom and upward phases. As with backward grinding, the point of minimum torque application for forward grinding (294°, 24 N m) was on the upward section and corresponded with a period during which only biceps brachii was notably active.

In addition to the importance of identifying causes of low torque zones or "dead spots" which can impact on performance, it is also of interest to examine where grinding biomechanics are optimum. In terms of maximum force application, peak torque was ~12% higher for forward grinding (77 N m) than for backward grinding (69 N m), which was consistent with previous findings where work performed over five seconds of maximal grinding was 12-15% greater in the forward direction [22]. Fujii & Nagasaki [21] also concluded that reverse arm cranking was less proficient than forward arm cranking. Peak torque occurred at 95° and 35° of crank angle for forward and backward grinding respectively, aligning with the end of shoulder horizontal flexion and elbow extension (push movement) in forward grinding, and at the completion of shoulder extension and elbow flexion (pull movement) in backward grinding. Although it has already been noted that forward grinding has a more even distribution of torque throughout the cycle, the location of the peaks does support the view that the primary "work generating" movements are upper body push and pull for forward and backward grinding respectively. However, it would appear that the importance of the areas of maximum torque application to the respective grinding directions also differs. Additional analysis on the relationship between torque application and performance showed that variation in torque throughout the grinding cycle was negatively associated with forward grinding performance ($r = -0.60$; CI -0.88 to -0.02) but positively associated with backward performance ($r = 0.48$; CI = -0.15 to 0.83). Although not a conclusive finding, what this does suggest is that while there may be justification in focussing on the primary pull movement (maximising the peak) to improve backward grinding performance, improvements in forward grinding are most likely to be achieved through the ability to maintain torque throughout the entire cycle. This observation would also seem to align with previous research into muscular performance characteristics where maximum muscular force was most closely related to forward grinding performance, while power and rate of force development were most important for backward grinding [35, 51]. While maximal strength and force were important in both directions, the additional importance of the speed of muscular performance for backward grinding was consistent with the torque profile observed with cyclic loading, unloading, and re-loading having to be repeated during a short period of time.

Overall, the disparities observed between the biomechanical characteristics of forward and backward grinding are somewhat at odds with similar research on cycling [50], which observed relatively little directional difference. Previous literature reporting EMG and kinematics (although not torque-angle curves) of seated arm-cranking [20] has shown more similar results, however it would seem that the additional degrees of positional freedom along with the potentially greater contribution of body weight allowed by the standing position used in grinding does impact the variation in biomechanics between cranking direction. This is reflected most notably in the differing torque-angle curves and observable at the most basic level by the different postural positions selected by the sailors when grinding backward versus forward, as compared to the relatively fixed position in seated arm cranking.

CONCLUSIONS

In terms of specific information that could potentially be used to improve performance, we have identified the movements and muscles involved in the grinding activity and the factors involved in periods of high and low torque. In many sporting movements it is the reduction in inefficiencies as much as maximum capability that determines overall proficiency and so it may be that working to improve the areas of weakness in the grinding cycle, whether through conditioning or technical changes, can improve grinding performance. However, further investigation would be required to determine whether this is in fact a practical solution or if it is the result of an unchangeable factor such as structurally limited function of the upper limb in that position. Even within the findings of this study there is evidence that the influence of biomechanical factors on performance differ according to direction, and as such any intervention would probably have to be customised between forward and backward grinding.

CHAPTER 5

KINEMATICS AND KINETICS OF THE BENCH PRESS AND BENCH PULL EXERCISES IN A STRENGTH-TRAINED SPORTING POPULATION

This chapter comprises the following paper has been accepted by *Sports Biomechanics*:

Pearson SN, Cronin JB, Hume PA, Slyfield D. Kinematics and kinetics of the bench press and bench pull exercises in a strength-training sporting population. Sports Biomechanics. 2009 September; 8(3):245–254.

(Author contribution percentages: SP: 83%, JC: 10%, PH: 5%, DS: 2%)

OVERVIEW

Understanding how loading affects power production in resistance training is a key step in identifying the most optimal way of training muscular power – an essential trait in most sporting movements. Twelve elite male sailors with extensive strength-training experience participated in a comparison of kinematics and kinetics from the upper body musculature, with upper body push (bench press) and pull (bench pull) movements performed across loads of 10-100% of one repetition maximum (1RM). 1RM strength and force were shown to be greater in the bench press, while velocity and power output were greater for the bench pull across the range of loads. While power output was at a similar level for the two movements at a low load (10% 1RM), significantly greater power outputs were observed for the bench pull in comparison to the bench press with increased load. Power output (P_{max}) was maximized at higher relative loads for both mean and peak power in the bench pull (78.6 ± 5.7% and 70.4 ± 5.4% of 1RM) compared to the bench press (53.3 ± 1.7% and 49.7 ± 4.4% of 1RM). Findings can most likely be attributed to differences in muscle architecture, which may have training implications for these muscles.

INTRODUCTION

Muscular power, the product of force and velocity [52-53], has been identified as an important factor in the performance of many sporting activities [53-56] and has been the subject of substantial research. Resistance training has been identified as one factor which plays an important role in the development of muscular power [57], although there is still considerable conjecture in the literature as to the most efficient method of achieving this goal [58]. In order to understand how muscular power can best be developed using resistance training, it is important to understand how the manipulation of different parameters can influence power output. One factor that is of particular interest is the influence of load, and in particular the load that maximizes muscular power output (P_{max}) [59-61]. P_{max} is considered by many researchers to be important in improving muscular power capability, and therefore the performance of various sporting movements, however, Cronin and Sleivert [59] have identified a number of issues within the current available research into the power-load relationship. Along with various methodological inconsistencies present in the literature (including contraction type, peak versus mean power), the variation in the power load spectrum and P_{max} load observed across populations and movements necessitates situation specific research and prohibits generalization of results [59, 62].

Within the sphere of power-load research to date, the vast majority of studies have been conducted using derivatives of two movements or exercises: the bench press exercise in the upper body [59, 63] and the squat in the lower body [59, 62]. While these exercises certainly represent key movements for many sporting activities, there are other movement patterns which also warrant examination. The bench pull, also known as the prone row, is another key multi-articular exercise used in the conditioning of athletes across a variety of sports [64-66], and as such a better understanding of the kinetic and kinematic characteristics of this movement will be of benefit to the neuromuscular development of athletes. The bench pull is essentially a direct contrast to the bench press movement, being performed by pulling the bar towards the chest from a prone horizontal position (shoulder extension, elbow flexion), compared to the supine, push-based motion of the bench press (shoulder flexion, elbow extension).

To date there has been no research examining the power-load relationship in the bench pull exercise, although one recent study has examined the similarly pull-based seated row [63] in elite rowers while Kawamori et al [67] studied the power-load relationship in the hang power clean, a whole body exercise with heavy dependence on upper body pulling. Some key differences were observed between the kinematics and kinetics of these pull-based exercise and those reported previously for the bench press. Most notable amongst these was the difference in the power-load relationship, with power output maximized at higher relative loads in the pull-based movements (row = 81% of 1RM; power clean = 70% of 1RM) compared to the push-based bench press. However, a limitation of both studies was that only the single movement was examined, and while there is considerable bench press research with which to draw comparison, issues with varying samples and methodologies mean that making certain assumptions and conclusions is problematic. The aim of this study therefore was to determine the power-load relationship of a push-based upper body shoulder horizontal flexion/push movement (bench press) and a pull-based extension/pull movement (bench pull/prone row) in a strength trained, sporting population. Examining this relationship in an identical population will enable a direct comparison of the power-load characteristics associated with each of these movements.

METHODS

Approach to the problem

This study was designed to examine and compare the biomechanical characteristics of the power-load relationship in the bench press and bench pull exercises. A Smith machine was instrumented to allow measurement of the kinematics and kinetics of the bar and weights during performance of the exercise. A spectrum of loads ranging from 10-100% of an individuals one repetition maximum (1RM) were used to model the full range power-load relationship by fitting a quadratic curve.

Subjects

Twelve elite-level male sailors from the Emirates Team New Zealand America's Cup syndicate participated in this study. As part of their sailing role all sailors performed grinding; a cyclic high load, high intensity upper body activity involving both push-based forward grinding and pull-based backward grinding. The sample size was small due to the elite nature of the participants, and therefore restricts the level of statistical power.

The sailor's mean (± SD) age, body mass, and height were 33.9 ± 5.5 years, 97.8 ± 12.5 kg, and 186.0 ± 7.1 cm. All participants had an extensive strength-training background (minimum of 3 years) and the bench press and bench pull exercises were commonly used as part of their training program. All subjects provided written, informed consent within the guidelines of the AUT University Ethics Committee (reference 04/221).

Equipment

Testing was performed on a modified Smith machine, which incorporates a bar fixed using low-friction linear bearings so that it can only slide vertically (Figure 12). A linear position transducer (Unimeasure, Oregon) was attached to the bar and measured bar displacement with an accuracy of 0.1 mm. These data were sampled at 500 Hz and relayed to a Labview (National Instruments, Texas) based acquisition and analysis program. It should be noted that although Smith machines are designed to be largely frictionless, the counterweight system will introduce some inertia to the system and as such this may influence the true resistance experienced by the athlete, however it was not thought that this should have a major influence on results.

Procedures

Each participant completed a 60-minute testing session involving both the bench press and bench pull exercises (Figure 13). Familiarisation was conducted through a self-determined, exercise-specific warm-up typically consisting of 3-4 warm-up sets of the particular exercise using progressively heavier loads. Following the warm-up the individuals' 1RM (Smith machine, concentric-only) was determined to the nearest 2.5 kg. The spectrum of loads for the power testing were then determined from 10-100% of 1RM at 10% intervals. Single repetitions of each load were performed in ascending order, with the instruction that each lift should be performed as explosively as possible without releasing the bar (in the bench press) – a fast but non-ballistic lift. All lifts were concentric-only, with the bench press initiated from mechanical stops positioned ~30 mm off the sailor's chest, and the bench pull initiated from a supported supine position. Two potential issues in regard to the presentation order of loads are the effects of fatigue and/or potentiation on later lifts in the sequence. In order to hopefully avoid such an occurrence each lift was separated by a rest period of 1-2 minutes (increasing with load), which was considered to be of a sufficient duration to minimise any order effects. Evidence that any possible fatigue effects were in fact minimal was confirmed by the sailor's ability to repeat their determined 1RM effort from the start of the session in the last of their ordered lifts (100% of 1RM), however the possibility of either fatigue or potentiation influencing the results, even if only in a small way, must be acknowledged.

Figure 12: Testing set-up for the power-load spectrum of the bench press exercise.

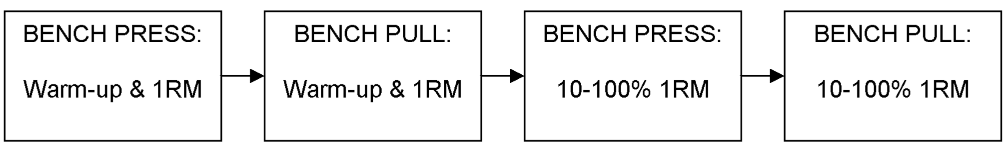


Figure 13: Structure of the testing session.

Data and statistical analyses

Displacement-time data were filtered using a low pass Butterworth filter with a cutoff frequency of 6 Hz, and then differentiated to determine instantaneous velocity, acceleration, force (using additional load information) and power output data over the range of motion for each load condition. It should be acknowledged that there is likely to be slight underestimation in the calculation of force, as it will not include the force required to overcome any friction of the Smith machine. However, as the Smith machine system is specifically designed to have low levels of friction it is expected that any effect is likely to be less than the biological variability of the user and therefore have minimal effect on the overall findings, an assertion supported by previous findings that the measures of force determined using this methodology have been previously validated and found to correlate highly with force plate measures across a range of movements, loads, and testing conditions [68-69].

Descriptive statistics for all variables are represented as mean and standard deviations. P_{max} values and power drop-off around P_{max} were calculated using the line estimation function (least squares method) in Microsoft Excel. Presence of significant systematic discrepancy between measures from the bench press and bench pull was determined using a two-tailed unpaired *t*-test (α level of $p \leq 0.05$).

RESULTS

Set-up specific determination of 1RM performance resulted in mean 1RM scores of 119.7 ± 23.9 kg for the bench press and 99.4 ± 15.4 kg for the bench pull. Table 9 displays the mean force, velocity, and power output values of all participants for the concentric phase of a single repetition for the bench press and bench pull across the range of relative loads. Mean force values were higher for the bench press/flexion movement while mean velocity values were greater for the bench pull/extension movement. In addition, while both movements followed the typical force-velocity relationship, the patterns of how these characteristics related to each other differed. Analysis of group means showed that force values maintained a linear relationship throughout the range of loads; with values for the bench pull approximately 17% lower relative to the comparative force values of the bench press. However, when bench pull velocity values were expressed relative to comparative bench press velocities they increased in an exponential manner as relative load increased; this exponential increase influencing the power output (see Figure 14). This resulted in the mean velocity for the concentric phase of the bench pull being 526% greater than the bench press at the 100% 1RM and mean power being 442% higher at the same load.

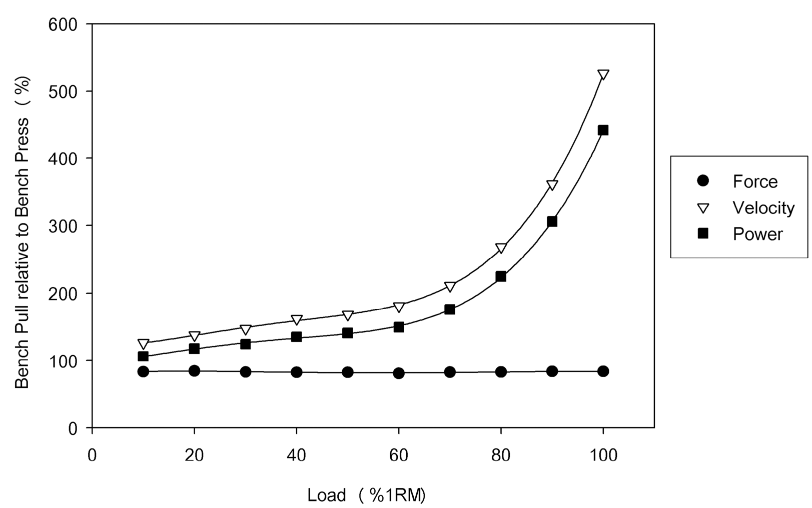


Figure 14: **Differences in the group means for force, velocity and power in the bench press and bench pull, with bench pull values presented as a percentage of equivalent bench press values.**

Table 9: Kinematic and kinetic measures (mean ±SD) for the bench press and bench pull exercises throughout a range of loads (%1RM).

Load	Bench Press			Bench Pull			P-value (difference)		
%1RM	Velocity (m/s)	Force (N)	Power (W)	Velocity (m/s)	Force (N)	Power (W)	Vel.	Force	Power
10%	0.95±0.14	122±29	117±36	1.20±0.16	102±15	125±32	0.001	0.055	0.615
20%	0.85±0.15	234±49	199±61	1.17±0.14	198±31	235±63	0.000	0.056	0.189
30%	0.72±0.10	354±70	253±57	1.06±0.12	293±45	315±80	0.000	0.027	0.051
40%	0.61±0.10	473±96	286±65	0.99±0.07	389±64	387±82	0.000	0.028	0.005
50%	0.52±0.10	592±124	306±75	0.88±0.05	488±75	432±82	0.000	0.030	0.001
60%	0.44±0.09	708±146	303±64	0.79±0.06	573±87	454±89	0.000	0.019	0.000
70%	0.34±0.05	829±167	284±64	0.73±0.04	685±103	499±88	0.000	0.026	0.000
80%	0.24±0.05	942±187	225±55	0.65±0.05	779±119	506±86	0.000	0.026	0.000
90%	0.15±0.04	1049±216	153±50	0.53±0.04	878±131	468±80	0.000	0.038	0.000
100%	0.09±0.03	1176±232	105±38	0.47±0.03	984±147	462±78	0.000	0.033	0.000

Note: Measurements are the mean value of the sample for the concentric phase of a single repetition.

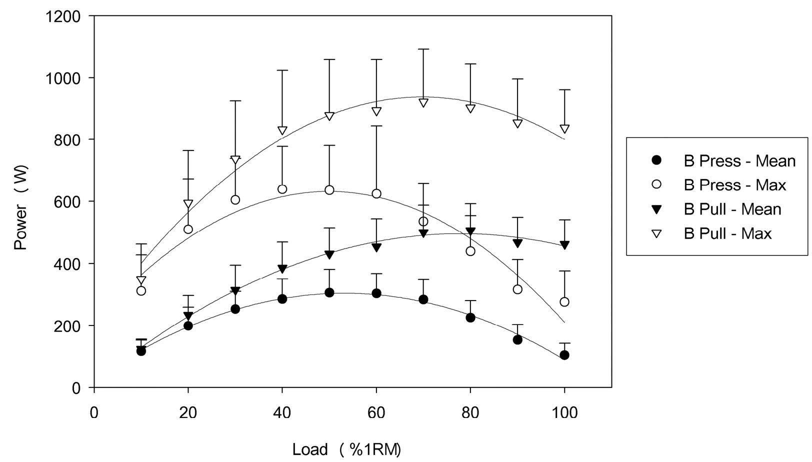


Figure 15: **Comparison of the power-load spectrum for the bench press and bench pull. Curves are presented for both mean and maximum power from a single repetition for all sailors (averaged).**

The average (across all participants) power output for bench press and bench pull across the spectrum of loads can be observed in Figure 15. Power was at a similar level for the two movements at low load (10% of 1RM), but with increasing load a substantially greater increase in power was observed for the bench pull in comparison to the bench press. Mean power output was maximised at a significantly higher load ($p<0.001$) for the bench pull (78.6 ± 5.7%1RM) than the bench press (53.3 ± 1.7%1RM). A similar disparity in P_{max} values were found for peak power, although the relative load at which maximum values occurred was significantly lower for both the bench pull (70.4 ± 5.4%; $p < 0.001$) and bench press (49.7 ± 4.4%; $p = 0.003$). In addition, reduction in power output either side of P_{max} was significantly lower for the bench pull at both 10% ($p<0.001$) and 20% ($p<0.001$) of load each side of P_{max}. Power output drop-off at 10% from P_{max} load was 1.6% for the bench pull and 3.2% for the bench press, while drop-off at 20% from P_{max} was 6.5% for the bench pull and 12.9% for the bench press.

DISCUSSION

The most notable finding of this study was the divergent power-load spectrum profiles of the bench press and bench pull. Muscular power output was higher for the bench pull throughout the entire load range, and significantly higher at loads of 40%1RM and over. This in itself was unexpected given the higher absolute loads (~17%) being lifted in the bench press, which should result in higher forces and generally be linked to higher power outputs, as is seen within exercises (stronger individuals having greater power output). Given that power is the product of force and velocity it would seem that the combination of these two variables in power production may be dependent on the muscles/movement used as evidenced in this agonist-antagonist pairing. Though speculative, the greater velocities and subsequent power outputs observed in the bench pull movement may be attributed to the differing muscle architecture. That is, previous research [70] has shown that the greater fibre lengths and longitudinal fibre arrangement of the primary movers used in exercises such as the bench pull exercise (i.e. latissimus dorsi, biceps brachii, brachialis) are characterised by faster shortening velocities, whereas the primary movers for exercises such as the bench press (i.e. pectoralis major, triceps brachii) are characterised by shorter fibre lengths, greater pennation angles, and subsequently greater force capability. For the bench pull it appears that, in terms of maximising power output at higher relative loads, the capability of the musculature used in the bench pull to generate greater force at higher shortening velocities greatly out-weighed the deficit in absolute force production compared to the bench press musculature.

Another explanation for the discrepancy between power outputs may be that the bench pull and bench press have different strength curves (mechanical advantages). Strength curves are classified into three categories: ascending, descending and bell-shaped, which are determined by the force-angle (torque) relationship within the musculoskeletal system [71]. Findings by Murphy et al. [72] indicate that the bench press has an ascending strength curve, meaning that maximum strength and greatest force production occurs near the apex of the lift. In comparison, individual muscle strength curves [71] suggest that the bench pull is a descending strength curve exercise where maximum strength is produced at the start of the lift. Given this relationship, the ability of the muscles to produce higher forces/accelerations earlier in the bench pull motion seemingly assist the relevant musculature to overcome the inertia of the load, which results in greater velocity and power output throughout the movement. Furthermore, this ability to overcome the inertial load seems of increasing advantage as load increases. It should be noted, however, that this discrepancy in power for the two movements may not be as great if a truly ballistic protocol was used, as the ability to continue accelerating the bar throughout the entire range of movement and then release would be greatly beneficial for an exercise with an ascending strength curve such as the bench press.

Further differences between exercises were also evident when the relative loads at which P_{max} occurred were compared. P_{max} loads for the bench press of around 50%1RM for both mean and peak power, along with a power output drop-off of ~3% for a 10% variation in load, were consistent with previous research which has reported P_{max} loads of 30-60%1RM in both the directly comparable concentric-only bench press [58, 73-74] as well as the more explosive rebound (stretch-shorten cycle) and throw bench press derivatives [75-78]. In contrast P_{max} occurred at a much heavier load for the bench pull; 78.6%1RM for mean power and 70.4% for peak power. Similar findings have been reported in the two other studies to examine the power-load spectrum in an upper body pull movement, with P_{max} for mean power occurring at 81% of 1RM in the seated row [63] and at 70%1RM for the hang power clean [67]. In addition, similar trends have been shown in-situ for a single muscle fibre, with Edgerton et al. [79] attributing the differences observed between power outputs and P_{max} loads in muscle groups of the lower limb to differences in muscle architecture (fibre length, type and arrangement). Although Edgerton et al. [79] reported flexor P_{max} (59%) to occur at a higher relative load than extensor P_{max} (45%) at the knee, the higher values again corresponded with the action involving more fusiform muscles with greater fibre length. In terms of these results it seems that the functional characteristics of the upper body “pull” musculature are indeed substantially different from those of the muscles responsible for the “push” movement. However, it should be noted that both the studies examining the upper body pull movement in vivo used elite, male, resistance-trained performers. Although it seems reasonably clear from the limited evidence available that P_{max} occurs at a higher relative load in upper body pull movements compared to push, it may not be possible to generalise the magnitude of these differences to other populations, especially given that P_{max} has been shown to be transient in relation to training status [59].

CONCLUSIONS

Force, velocity and power generating characteristics of the shoulder extensor and elbow flexor muscles responsible for the bench pull movement were substantially different from the shoulder flexor and elbow extensor muscles responsible for the bench press. The bench pull produced greater velocities and power outputs, along with exhibiting a higher relative load for P_{max} – findings which may be due to differences in muscle architecture. The disparate characteristics of the upper body push and pull movements examined in this study may have implications in terms of the way different muscle groups or movement patterns are trained. In particular it may be pertinent to advocate higher relative loads in resistance training in upper body pull (compared to push) movements where power development is of importance, however further training studies are necessary to validate this recommendation.

When targeting power in resistance training exercises, key points for consideration from this study are:

1) P_{max} is not only individual but also exercise specific and needs to be assessed in such a manner.
2) Different loads are required to maximise peak and mean power so the functional significance of each must therefore be evaluated with training design.

In terms of the specific (sailing) population used in this study, it is possible that greater performance benefits can be derived by altering upper body training loads for forward (push-based) and backward (pull-based) grinding in order to more efficiently stimulate the development of muscular power.

CHAPTER 6

STRENGTH AND POWER DETERMINANTS OF GRINDING PERFORMANCE IN AMERICA'S CUP SAILORS

This chapter comprises the following paper accepted by *Journal of Strength and Conditioning Research*:

Pearson SN, Cronin JB, Hume PA, Slyfield D. Strength determinants of grinding performance in America's Cup sailors. Journal of Strength and Conditioning Research. 2009; 23(6):1883-1889.

(Author contribution percentages: SP: 80%, JC: 10%, PH: 5%, DS: 5%)

OVERVIEW

Grinding is a physically demanding component of America's Cup sailing which is important to overall team performance but little research is available on the determinants of grinding performance. We examined the relationship between various measures of muscular performance and the performance of upper body grinding. Eleven elite male America's Cup sailors (33.9 ± 5.5 years, 97.8 ± 12.5 kg, 186.0 ± 7.1 cm) who performed grinding as part of their on-board role and with extensive strength-training experience participated in this study. Muscular performance testing examined the force, velocity, and power capabilities of the upper body musculature, with upper body push (bench press) and pull (bench pull) movements performed across loads of 10-100% of one repetition maximum (1RM). Functional grinding performance was examined for both forward and backward grinding and at two different resistances (moderate = 48 N m, heavy = 68 N m) using a land-based ergometer. Bench press 1RM and maximum force capability were the measures demonstrating the strongest correlation with forward grinding performance (r = 0.88-0.99 and 0.87-0.99 respectively) with the relationship increasing with grinding load. For backward grinding, there was a very strong relationship with bench pull maximum power (r = 0.85-0.98) in addition to 1RM (r = 0.90-0.95) and max force (r = 0.87-0.95). It appears that while maximal strength is a crucial muscular performance characteristic for grinding performance in all conditions, for backward grinding there is the additional need to focus on the development of speed-strength/power to maximize performance gains. This information was used by the Emirates Team New Zealand physical conditioner to develop a conditioning intervention to help improve grinding performance.

INTRODUCTION

Muscular capability is a major factor in determining performance across almost all sporting and athletic events. Resistance training has long been established as playing an important role in the development of muscular capability [57], however, depending on the specific demands of the event in question the muscular requirements for performance and therefore the type of training required for enhancement will differ [60, 80]. Understanding which muscular characteristics (e.g. strength or endurance; force, velocity or power) are most important for the performance of a specific event is a key issue in maximizing the transfer of training to performance, and therefore improving training efficiency [81]. Such an approach has been used in a variety of sports such as soccer [82], rugby [83] and athletics [84] however there is a general paucity of research into the strength and power requirements of yachting performance.

The America's Cup is widely regarded as the pinnacle of sailing competitions and, as such, considerable resources are put into improving the performance of the America's Cup yachts (Figure 16) and the sailing teams. One important physical aspect of on-water sailing performance is grinding, a cyclic, high load, high intensity upper body task which provides the power behind tacking and gibing and influences the efficiency of wind usage through movement of the sails. The grinding handles are situated on top of an 87 cm pedestal, and are at the end of two cranks, which are orientated at 180 degrees from each other, one on either side of the pedestal, making the overall set-up similar to an upper limb bicycle. Sailors perform grinding in both a forward direction – pushing away from their body at the top of the rotation and backward direction – pulling towards their body at the top of the rotation, depending on the gear in use.

With regards to resistance training, the movement patterns used in forward and backward grinding correspond well with the bench press and bench pull (prone row) exercise respectively. Previous research has found grinding performance to correlate strongly with maximal strength in these two exercises, with the relationship increasing when grinding is performed against a higher load [85]. However, those results were based on one-repetition maximum (1RM) scores predicted from training data and offer little in terms of whether certain kinetic or kinematic factors related to maximal strength may be more or less important to performance, which may in turn have implications for resistance training programming.

Figure 16: An America's Cup yacht during test racing.

Purpose

The purpose of this study was to examine the relationship between forward and backward grinding performance and the kinetic and kinematic characteristics of the bench press and bench pull exercises. This information can be used by physical conditioners to better advise best practice for conditioning for grinding performance.

METHODS

Experimental approach to the problem

This study was designed to examine the relationship between grinding performance and the characteristics of the power-load relationship in the bench press and bench pull exercises. Forward and backward grinding performance was assessed using a custom-made grinding ergometer. A Smith machine was instrumented to allow measurement of the kinematics and kinetics of the bar and weights during performance of the bench press and bench pull exercises.

Subjects

Eleven elite-level male sailors from the Emirates Team New Zealand syndicate (who competed in the final of the 2007 America's Cup) participated in this study. All sailors performed grinding as part of their on-board sailing role. All participants had an extensive strength-training background (minimum of 3 years) and the bench press and bench pull exercises were commonly used as part of their training program. Sample size was small for a correlational study due to the elite nature of the participants, and therefore restricts the level of statistical power.

The sailor's mean (± SD) age, body mass, and height were 33.9 ± 5.5 years, 97.8 ± 12.5 kg, and 186.0 ± 7.1 cm. All participants provided written, informed consent within the guidelines of the AUT University Ethics Committee (reference 04/221).

Equipment

Grinding performance testing was conducted on a grinding ergometer (Dynapack, Wellington, NZ) with standard pedestal (870 mm vertical) and crank arm (250 mm) dimensions for a main sheet grinding pedestal on an America's Cup class yacht (see Figure 17). Gearing for the ergometer was linked through a multiple-speed dynamometer set up to output a number of grinding performance measures. Power output was obtained from the grinding ergometer using a bi-directional oil hydraulic system custom designed to meet the tactile characteristics of the rigging at the grinding station. Speed was based on a 24-slot disc attached directly to the motor input shaft. Output was obtained via an analogue to digital converter using 8-bit resolution to a C++ customised data collection system sampling at 40 Hz. Mechanical load was varied using a custom designed cog selector allowing 1:1 and 3:1 ratios driven by toothed belts. Hydraulic load was applied using a dynamic closed loop controller modified to operate at low speed. Calibration was performed using calibrated masses and known lever lengths, and the machine was verified accurate to 0.5% or better throughout its range. Reliability of external work (SEM = 1.6-6.9%; ICC = 0.91-0.99) as a grinding performance measure using this ergometer has previously been reported [22].

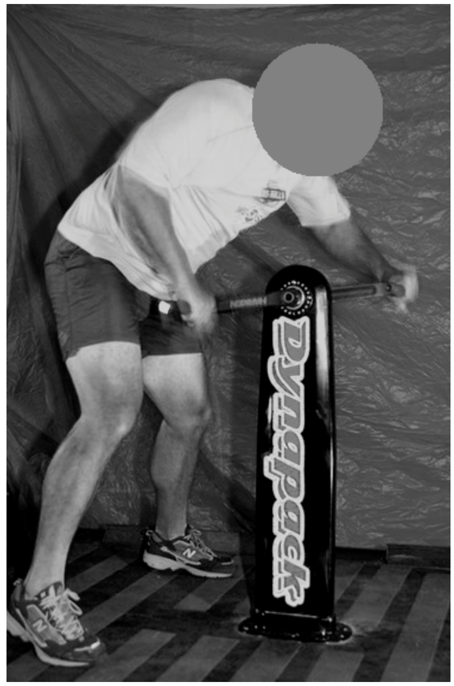


Figure 17: Sailor on the grinding ergometer during performance testing.

Biomechanical strength characteristics in the bench press (supine position) and bench pull (prone position) were tested using a modified Smith machine (Figure 18). A linear position transducer (Unimeasure, Oregon) was attached to the bar and measured bar displacement with an accuracy of 0.1 mm. These data were sampled at 500 Hz and relayed to a Labview (National Instruments, Texas) based acquisition and analysis program. The data acquired from the linear transducer in this testing setup have been reported previously as reliable (ICC = 0.92–0.98) and valid across a range of movements and testing conditions [69].

Figure 18: Testing set-up for the power-load spectrum of the bench press exercise.

Procedures

Prior to testing sessions, sailors had a minimum of one day of rest without any training. The usual team protocols prior to training for nutrition, hydration and sleep were followed and were the same prior to both testing sessions. Grinding and strength performance testing were performed on separate days within seven days of each other. Both forward and backward grinding performances were tested using two torque loading conditions; 48 N m (Moderate), and 68 N m (Heavy). Testing loads were selected to mimic moderate- and high-load conditions during on-water grinding manoeuvres, based on rpm ranges for a primary grinder. All 11 sailors completed the moderate load but due to the physical requirements for grinding effectively at the heavy load only the six sailors regarded as principal grinders (i.e., their main on-board responsibility is grinding) completed the heavy load condition. Sailors completed a self-determined warm-up on the grinding ergometer prior to testing, with testing consisting of two trials of each condition. Trials were maximal, of eight seconds duration, and separated by five minutes and alternated between forward and backward grinding to reduce the possible influence of any fatigue effects.

For strength-power testing each sailor completed a 60-minute testing session involving both the bench press and bench pull exercises. Familiarisation was conducted through a self-determined, exercise-specific warm-up typically consisting of 3-4 warm-up sets of the particular exercise using progressively heavier loads. Following the warm-up the individuals' 1RM (Smith machine, concentric-only) was determined to the nearest 2.5 kg. The spectrum of loads for the power testing were then determined from 10-100% of 1RM at 10% intervals. Single repetitions of each load were performed in ascending order, with the instruction that each lift should be performed as explosively as possible without releasing the bar. All lifts were concentric-only and non-ballistic (no bar release), with the bench press initiated from mechanical stops positioned ~30 mm off the sailor's chest, and the bench pull initiated from a supported supine position. Each lift was separated by a rest period of one to two minutes (increasing with load), which was considered sufficient to avoid or minimise any fatigue effects. Evidence that any possible fatigue effects were minimal was confirmed by the sailor's ability to repeat their determined 1RM effort from the start of the session in the last of their ordered lifts (100% of 1RM).

Data analyses

Raw power values were calculated by the Dynapack ergometer software using the formula: Power (W) = Torque x (2π*rpm)/60. The raw power curve was then smoothed using a second order recursive Butterworth low pass filter and peak power and external work calculated using a customised Labview program. For grinding performance the measure of interest to this study was external work performed (kJ), the five-second integral of the area under the power output curve, starting at the occurrence of peak power. External work has previously been shown to be a more reliable performance measure than peak power on this grinding ergometer [22].

Displacement-time data from the linear transducer used in strength-power assessment were filtered using a low pass Butterworth filter with a cutoff frequency of 6 Hz, and then differentiated to determine instantaneous velocity, acceleration, force (using additional load information) and power output data over the range of motion for each load condition. Measures of force determined using this methodology have been previously validated and found to correlate highly with force plate measures across a range of movements and testing conditions [68-69]. Variables of interest from the strength-power testing were 1RM, maximum force, maximum velocity and maximum power across the spectrum of testing loads, and the load (%1RM) at which power was maximised (Pmax). Force, velocity and power were all calculated as the mean concentric value during the concentric phase of the analysed repetition.

Statistical analyses

Descriptive statistics for all variables are represented as mean and standard deviations. For the power-load spectrum, Pmax values (load and power output) were calculated using the line estimation function (least squares method) in Microsoft Excel. Relationships between individual characteristics and grinding performance were analysed using Pearson correlation analysis and Cohen's magnitude of effect scale [46]. The influence of individual characteristics on grinding performance was examined using stepwise linear regression in SPSS (v13.0) with grinding performance as the dependent variable. Default probability criteria for the model were retained for entry ($F \leq 0.050$) and removal ($F \geq 0.100$). Presence of significant systematic discrepancy between measures from the bench press and bench pull was determined using a two-tailed unpaired *t*-test (α level of $p \leq 0.05$).

RESULTS

Grinding performance data for the four conditions examined are presented in Table 10. Tables 2 and 3 display the mean values for each of the strength-power variables of interest along with their correlation with grinding performance. Table 4 contains individual data for the 1RM and power variables.

Table 10: Performance results for forward and backward grinding at two loads. Means and standard deviations (SD) are shown.

Grinding direction	Moderate load (48 N m) *n = 11*	Heavy load (68 N m) *n = 6*
Forward (kJ)	107.1 (11.4)	124.6 (26.7)
Backward (kJ)	99.0 (11.4)	108.2 (27.9)

The results for forward grinding in Table 11 show very large significant ($p < 0.01$) positive correlations between both 1RM and the force able to be produced for the bench press ($r = 0.87$ to 0.99), with a stronger relationship when grinding against a heavy load compared to grinding against a moderate load. Velocity capability showed no significant relationship to forward grinding performance. Power capability and the relative load at which maximum power (in the bench press) was generated both showed moderate-large (r = 0.49 to 0.55) but non-significant relationships with grinding performance. Power capability was positively associated with grinding performance while Pmax load was negatively associated.

Table 11: Relationship between strength-power measures from the bench press and forward grinding performance at two different loads. Mean and standard deviation (SD) are shown for independent variables and Pearson correlations with associated p-values indicate relationship with performance.

Variable	Mean (SD) *n = 11*	Correlation with moderate load (p-value)	Mean (SD) *n = 6*	Correlation with heavy load (p-value)
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)

The results from the bench pull testing and their relationship to backward grinding performance are detailed in Table 12. As with forward grinding, 1RM and force capability demonstrated the largest correlations with moderate load performance (r = 0.87 to 0.95), however power capability also had a very large, significant correlation and showed the strongest relationship with heavy load performance (r = 0.85 to 0.98). Velocity capability showed a very large positive correlation with heavy load backward grinding performance (r = 0.97) although only a moderate-large non-significant correlation with performance at lower (moderate) load (r = 0.56). Pmax load had a similar (moderate, negative) correlation with backward grinding performance as with forward grinding.

Table 12: Relationship between strength-power measures from the bench pull and backward grinding performance at two different loads. Mean and standard deviation (SD) are shown for independent variables and Pearson correlations with associated p-values indicate relationship with performance.

Variable	Mean (SD) *n = 11*	Correlation with moderate Load (p-value)	Mean (SD) *n = 6*	Correlation with heavy Load (p-value)
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)

Table 13: Individual 1RM and power measures from the bench press and bench pull, with correlations (*r*) of power variables with 1RM for each exercise.

	Bench Press			Bench Pull		
Sailor	1RM (kg)	Pmax (W)	Pmax load (%1RM)	1RM (kg)	Pmax (W)	Pmax load (%1RM)
1	108	309.8	54.9	104	501.9	71.9
2	104	288.7	53.7	86	401.7	86.7
3	99	262.0	52.9	81	434.3	77.5
4	123	182.1	53.4	100	483.5	85.5
5	92	253.3	53.6	88	427.3	86.1
6	115	320.4	51.3	95	449.6	74.3
7	165	413.1	52.0	124	670.7	77.0
8	114	295.3	53.9	94	486.2	76.3
9	105	277.0	56.0	84	434.9	81.9
10	138	422.7	54.0	119	593.7	70.8
11	158	326.8	50.1	120	606.4	76.2
r		-0.603	0.634		-0.522	0.962
(p-value)		(0.050)	(0.036)		(0.099)	(0.000)

Stepwise regression did not add considerably to the results in Tables 12 and 13, with maximal strength (represented as 1RM) being the key predictor of forward grinding performance. Bench press 1RM and maximum force explained 87% of performance variation for moderate load forward grinding (1RM only: r^2 = 0.753; 1RM + max force: r^2 = 0.866), while 1RM alone explained 97% (r^2 = 0.966) of heavy load forward grinding performance. For backward grinding, 1RM was still the key predictor in moderate load performance (r^2 = 0.796); however power capability showed the greatest common variance with grinding performance at the heavy testing load (r^2 = 0.960).

DISCUSSION

Bench press 1RM and bench press maximum force were the two strongest predictors of forward grinding performance, with the relationship improving as grinding load increased. In the stepwise linear regression model used for this data, 1RM and force together explained 87% of the inter-sailor variation in forward moderate load grinding, while 1RM by itself explained 97% of the variation in forward heavy load grinding. While power had moderate correlations (r=0.49 to 0.55), the ability to generate bar velocity in the bench press had a trivial relationship with forward grinding performance. It seems that maximal strength, rather than power, is the muscular characteristic most related to forward grinding performance.

For backward grinding and bench pull, the maximal strength variables (1RM, force) still had very strong relationships with grinding performance, however, the ability to generate power and velocity seemed to be comparatively much more important than for forward grinding. While 1RM was still the best predictor of medium load backward grinding performance (explaining 80% of inter-sailor variation), the relationship for power was similar (correlation of r = 0.85 for power versus r = 0.90 for 1RM). Furthermore, for heavy load backward grinding, both power (r = 0.98) and velocity (r = 0.97) had slightly stronger relationships with performance than 1RM or force (r = 0.948 for both). This also showed in the regression model where power capability explained 96% of inter-sailor performance variation by itself. It should be noted that there were only six sailors in the heavy load grinding group, and lower numbers tend to decrease the precision of statistical analyses and increase the likelihood of unusual findings. However, the prominence of power and velocity as predictors of backward grinding performance indicates that, in this instance, the ability to continue generating force and impulse at high contraction velocities is probably more important than the actual quantity of force.

A possible explanation for the different relationships for forward and backward grinding is the difference in muscle architecture (fibre length, type, arrangement, etc) between the flexor/"pull" muscles used for the bench pull and the extensor/"push" muscles (bench press). The greater fibre lengths and longitudinal fibre arrangement of the primary movers in the bench pull exercise (latissimus dorsi, biceps brachii, brachialis) are characterised by faster shortening velocities, whereas the primary movers for the bench press (pectoralis major, triceps brachii) have shorter fibre lengths, greater pennation angles, and subsequently greater force capability [70]. This theory would appear to be consistent with the higher power outputs and higher Pmax load (%1RM) for bench pull compared to the bench press observed here.

What these findings suggest is that there is probably merit in training the push and pull components of grinding differently. The resistance training regime for the sailors involved in this study was primarily focussed around improving maximal strength/force generation as this was understandably (and correctly) viewed as a key factor in grinding performance. While the findings from this study fully support that approach for enhancing forward grinding, it may be that greater performance improvements could be made in backward grinding by incorporating a greater velocity or power component in the training programme, while maintaining the maximal strength base that is still crucial for backward grinding performance.

One additional factor which should be addressed with regard to possible training stimulus for improving power is the relevance of the load at which the mechanical power output of the muscle is maximised. There is a school of thought that this may be important maximising power and performance gains [59] and this has been shown to be the case in some instances [60]. While the findings from this study cannot contribute in any definitive manner to this particular question it is worth noting that the relationship between power capability and Pmax load was moderate for the bench pull (r = -0.529, p = 0.094) and negligible for the bench press (r = -

0.199, p = 0.558). When combined with the moderate negative correlations of Pmax load with performance (Tables 11 and 12) and 1RM (bench press: r = -0.603, p = 0.050; bench pull: r = -0.522, p = 0.099) this indicates that as an individual's training status advances and they become stronger or more powerful, the relative load at which power is maximised decreases. It has been observed from previous research that relative Pmax load is transient [59], and while the findings from this study support that conclusion, they do suggest that it may in fact be more a case of strength and power capability being transient and changing with training, while the absolute load that maximises power remains constant, resulting in a lower relative load.

PRACTICAL APPLICATIONS

It is apparent from this study that the strength-power characteristics that determine grinding performance differ between the push-based forward grinding and the pull-based backward grinding. While maximal strength and force production capability are crucial attributes across all grinding conditions examined here, for backward grinding the need to be able to produce this force at speed (power) at least matches, if not surpasses maximal strength as the most important muscular function characteristic. It therefore seems possible that greater benefits for backward grinding performance can be derived by altering the training stimulus for upper body pull-based resistance exercises in order to more efficiently stimulate the development of muscular power in addition to maximal strength. This information was later used by the Emirates Team New Zealand physical conditioner to develop a conditioning intervention to help improve grinding performance.

CHAPTER 7

EFFECTS OF A POWER-FOCUSSED RESISTANCE TRAINING INTERVENTION ON BACKWARD GRINDING PERFORMANCE IN AMERICA'S CUP SAILING

This chapter comprises the following paper accepted by *Sport Biomechanics*:

Pearson SN, Cronin JB, Hume PA, Slyfield D. Effects of a power-focussed resistance training intervention on backward grinding performance in America's Cup sailing. Sports Biomechanics. 2009; in press.

(Author contribution percentages: SP: 80%, JC: 10%, PH: 5%, DS: 5%).

OVERVIEW

This study determined whether backward grinding performance in America's Cup sailing could be improved using a six-week training intervention to increase power capability in the upper-body pull movement. Fourteen elite male sailors (34.9±5.9 years; 98.1±14.4 kg; 186.6±7.7 cm) were allocated into experimental (speed-focussed) and control groups. Grinding performance was assessed using a grinding ergometer and an instrumented Smith machine measured force, velocity and power during the bench pull exercise. Conventional training produced significant improvements in bench pull 1RM (5.2±4.0%; $p = 0.016$) and maximum force production (5.4±4.0%; $p = 0.014$). Speed-focussed training improved maximum power (7.8±4.9%; $p = 0.009$), power at 1RM (10.3±8.9%; $p = 0.019$) and maximum velocity (8.4±2.6%; $p = 0.0002$). Backward grinding performance showed greater improvements in the experimental group than the control group for moderate (+1.8%) and heavy load (+6.0%) grinding. Changes in maximum power output and power at 1RM had large correlations ($r = 0.56$-0.61) with changes in both moderate and heavy load grinding performance. Time to peak force had the strongest relationship, explaining 70% of the change in heavy load grinding performance. Although the performance benefit was not entirely clear the likelihood of a detrimental effect was low (<5%) and therefore implementation could be recommended.

INTRODUCTION

Grinding is a cyclic, high load, high intensity upper body task in America's Cup sailing which involves the manual hand cranking of winches attached to the sail lines responsible for the movement of the sails. Functionally, grinding provides the power behind tacking and gibing and influences the efficiency of wind usage, making it a key factor in competition performance. The handles used for grinding are situated on top of an 87 cm pedestal, and are at the end of two cranks which are orientated at 180 degrees from each other, one on either side of the pedestal, making the overall set-up similar to an upper limb bicycle (see Figure 19). Gearing set-up of the grinding winches means that sailors are required to perform grinding in both a forward direction – pushing away from their body at the top of the rotation; and backward – pulling towards their body at the top of the rotation. The most recently used (version 5) America's Cup class yachts featured four grinding pedestals, each of which is usually manned by two sailors during use [1]. This means that during any instance of active grinding there will be sailors performing both forward and backward grinding at each grinding pedestal, putting even weighting on each with regards to overall boat performance.

Figure 19: Ergometer for grinding performance testing.

There is a lack of scientific research available on America's Cup grinding, although there are a number of papers on the kinematically similar seated arm cranking exercise [38, 86] which is often used in rehabilitation of shoulder injury and wheelchair users [20]. Observational studies have shown that performance in grinding or arm cranking has been influenced by grinding direction [20-22] and system resistance [22-23]. To the authors knowledge there have be no studies on how grinding performance might be improved, however, improved physical conditioning in the form of resistance training would appear to be one possibility.

Resistance training plays an important role in the development of muscular capability [57], which is a major factor in determining performance across most athletic events. Muscular requirements for performance and therefore the type of training required for enhancement will differ depending on the specific demands of the event in question [60, 80]. Previous research with America's Cup grinding has found that performance correlates strongly with one repetition maximum (1RM) for bench press (forward grinding) and bench pull (backward grinding) exercises [85]. More specifically forward grinding was closely related to maximal strength/force production capability and backward grinding was closely related to power/speed-strength [35]. There may be merit in training the upper body push movements (for forward grinding) differently to the upper body pull movements (for backward grinding) in order to maximize the transfer of training to performance; an important factor in improving training efficiency [81].

It appears there may potentially be performance benefits for backward grinding from pursuing a more power-oriented training focus using upper body pull movements. The present experiment was therefore devised to determine whether backward grinding performance could be improved by increasing power capability in the upper body pull movement via a more speed-focussed resistance training stimulus.

METHODS

Participants

Fourteen elite-level male sailors from the Emirates Team New Zealand America's Cup syndicate were randomly allocated using a matched pair design into two training groups (n = 7), an experimental group and a control group. Groups were matched for pre-intervention strength, backward grinding performance, body mass and sailing role. All sailors had an extensive strength-training background (minimum of 3 years) and the bench pull exercise was commonly used as part of their training program. Prior to our study the primary conditioning of the sailors involved in this research was focussed on maximal strength development, which most likely advantaged forward grinding performance. Sample size was small due to the elite nature of the participants, and therefore restricts the level of statistical power, as the recommended sample size for this type of study was calculated as 26 in each group using the methods of Hopkins [87] with type 1 and type 2 errors of 5% and 20% respectively. Unfortunately the recommended sample size was not practically attainable.

In each group all seven sailors completed grinding performance testing at the moderate load but only eight sailors (n = 4 per group) completed testing at the heavy load due to the physical strength required for this task. Sailor characteristics are presented in Table 14. All sailors provided written informed consent within the guidelines of the AUT University Ethics Committee (reference 04/221).

Table 14: Pre-intervention characteristics of the two training groups (mean ±SD).

	Body Mass (kg)	1RM Bench Pull (kg)[1]	Grinding performance (kJ)[2]
Control (n = 7)	98.2±14.0	113.1±21.2	92.2±10.3
Experimental (n = 7)	97.9±15.9	114.4±19.5	91.3±13.3
Difference (%)	*-0.3 (0.3%)*	*1.3 (1.1%)*	*-0.9 (-1.0%)*
Heavy Control (n = 4)	106.9±10.6	123.5±22.5	97.8±7.8
Heavy Expt. (n = 4)	106.0±14.1	123.8±19.4	98.5±9.1
Difference (%)	*-1.0 (0.9%)*	*0.3 (0.2%)*	*0.7 (0.7%)*

[1] Predicted 1RM determined during routine strength testing.

[2] Backward performance at the moderate load (48 N m) as this was completed by all sailors.

Equipment

Grinding performance testing was conducted on a grinding ergometer; the technical specifics and reliability have previously been reported [22]. The ergometer was set up with standard pedestal (87 cm vertical) and crank arm (25 cm) dimensions for a main sheet grinding pedestal on an America's Cup class yacht (see Figure 19).

Kinematic and kinetic characteristics of the sailors' strength (force, velocity, and power) were determined for the bench pull exercise using a modified Smith machine. A linear position transducer (Unimeasure, Oregon) attached to the bar measured bar displacement with an accuracy of 0.1 mm. Data were sampled at 500 Hz and relayed to a Labview (National Instruments, Texas) based acquisition and analysis program. Data acquired from the linear transducer in this testing setup have been reported previously as reliable (ICC = 0.92–0.98) and valid across a range of movements and testing conditions [69]. A similar procedure was used to collect gym-based training data during weeks five and six of the intervention period for monitoring purposes[1]; the one point of difference being that gym-based bench pull training was performed using an un-constrained free barbell as opposed to a Smith machine.

Procedures

Sailors were tested for backward grinding performance and bench pull performance twice; first in the week immediately preceding the training intervention and second in the week immediately following the completion of the six-week intervention.

Testing was conducted on a grinding simulator in a manner familiar to the sailors, as the protocol was the same as for grinding testing performed regularly as part of their fitness monitoring. Sailors completed a self-determined warm-up on the grinding ergometer prior to testing, which consisted of three maximal-effort grinds of eight-seconds separated by a rest period of at least two minutes. Backward grinding performance was tested using two torque loading conditions; 48 N m (Moderate) and 68 N m (Heavy). Testing loads were selected to replicate moderate- and high-load conditions during on-water grinding manoeuvres, based on rpm ranges for a primary grinder.

For bench pull strength-power testing each sailor completed a 30-minute testing session using the instrumented Smith machine. As sailors were already familiar with the bench pull exercise only a short, set-up specific familiarisation was conducted, via a warm-up. Warm-up was performed on the testing equipment in a manner self-determined by the sailor, but typically consisting of 3-4 warm-up sets using incrementally heavier loads. Following the warm-up, specific 1RM (Smith machine, concentric-only bench pull) was determined to the nearest 2.5 kg. The spectrum of loads for the power testing were then determined from 10-100% of 1RM across 10% intervals. Single repetitions of each load were performed in ascending order, with the instruction that each lift should be performed as explosively as possible without releasing the bar. All lifts were concentric-only, initiated from full arm extension in a supported prone position. Each lift was separated by a rest period of 1-2 minutes (increasing with load), which was considered sufficient to minimise any fatigue. Evidence that any possible fatigue effects were

[1] Data are only provided for weeks 5 and 6 as this was when the sailors were training with the highest loads. As such, the differences should have been the smallest (i.e. worst case scenario for differences between the groups).

minimal was confirmed by the sailor's ability to repeat their determined 1RM effort from the start of the session in the last of their ordered lifts (100% of 1RM).

Intervention

Sailors completed a six-week training intervention period. Weight training programmes across all participating sailors were of a standard periodised structure (see Table 15), based on repetitions (reps) to failure. The programme consisted of three strength training sessions per week of which two included "pull" movements. Although there was some variation in specific exercises performed according to sailing role (e.g. seated cable row, chin-ups, dumbbell bent-over row), bench pull was common to all programmes.

Table 15: Weight-training loading structure for the six-week intervention period.

Weeks	Pull sessions	Reps to failure	Work sets
1-2	2	8-10	3 sets, short rest
3-4	2	5-7	3 sets, moderate rest
5-6	2	3-4	2 sets, long rest

Short rest = 45-90 seconds; Moderate rest = 1-2.5 minutes; Long rest = 2-5 minutes. Short end of the rest ranges were used for exercises involving the least muscle mass and the long end of the rest ranges were used for exercises involving the most muscle mass.

The only substantial difference between the training groups was the instruction given on how exercises should be performed. Sailors in the experimental group were instructed to perform upper body pull-based exercises (shoulder extension/elbow flexion) explosively, moving the loads as quickly as possible through the concentric phase. In contrast, the control group completed their normal/conventional training, with the movements performed with the concentric phase at a controlled, steady pace (approximately 1-2 second duration). By limiting the difference in the training stimulus to purely the temporal characteristics of the lifts, the influence of confounding factors such as differences in volume and intensity were negated.

Data analyses

Raw power values for grinding performance were calculated by the Dynapack ergometer software using the formula: Power (W) = Torque x (2π*rpm)/60. Raw power curves were smoothed using a second order recursive Butterworth low pass filter with a cutoff frequency of 6 Hz, and peak power and external work calculated using a customised Labview program. Total work (J) performed during the five-second period from peak power was determined for each grinding performance trial, and the three-trial mean calculated. External work has been shown to be a more reliable performance measure than peak power [22].

Displacement-time data from the linear transducer used in the strength-power assessment were filtered using a low pass Butterworth filter with a cutoff frequency of 6 Hz. Displacement-time data were differentiated to determine instantaneous velocity and acceleration, and in conjunction with the mass lifted, force and power output data over the range of motion for each load were determined. Measures of force determined using linear transducer methodology have been validated and correlate highly with force plate measures across a range of movements and testing conditions [68-69].

For each repetition across the load spectrum the mean velocity, force, and power for the concentric phase were calculated, along with the time to peak force within each repetition. Values were taken from three points across the load spectrum for further analysis: 1) at 100% of 1RM load (1RM); 2) at the load that maximised mean power output (Pmax); and 3) the maximum value across the 10 loads tested (max). It should be noted that for the time to peak force, the shortest time was regarded as the "maximum" value.

Statistical analyses

Descriptive statistics for all variables are represented as mean and standard deviations. Presence of significant systematic discrepancy between groups was determined using a two-tailed unpaired *t*-test with an α level of $p \leq 0.05$, adjusted to $p \leq 0.02$ using the Bonferroni correction for multiple independent comparisons. To make inferences about true (population) values of the effect of the training intervention on performance, data was log-transformed to account for non-normalised spread and the uncertainty in the effect was expressed as likelihoods that the true value of the effect represents substantial change (harm or benefit) using the methods of Hopkins [88]. The smallest worthwhile change set as 0.20 standardised (Cohen) units and confidence limits set at 90%. The relationships between changes in strength-power variables and the change in grinding performance were examined using Pearson correlation analysis, coefficients of determination (R^2), and Cohen's magnitude of effect scale [46].

RESULTS

Table 16: Speed-related training data (mean ± SD) for each group during weeks five and six of the intervention period.

	Control (n = 7)	Experimental (n = 7)	Inter-group p-value
Work set 1			
Load lifted (kg)	96.7 ± 20.9	92.9 ± 19.5	0.742
Concentric time (s)	0.98 ± 0.14	0.86 ± 0.11	0.001
Mean concentric velocity (m/s)	0.53 ± 0.07	0.60 ± 0.10	0.003
Work set 2			
Load lifted (kg)	95.8 ± 14.6	92.9 ± 13.5	0.712
Concentric time (s)	1.01 ± 0.14	0.92 ± 0.18	0.031
Mean concentric velocity (m/s)	0.53 ± 0.08	0.55 ± 0.10	0.444

Differences in training speed

Load lifted, concentric lift time and lift velocity from training are presented in Table 16. Time taken to complete the concentric phase was significantly shorter in the experimental group by ~0.1 seconds for both heavy work sets. Mean velocity for the concentric phase was significantly higher (+0.07 m/s) for the experimental group during the first work set but only marginally higher (+0.02 m/s) in the second set.

Table 17: Mean (±SD) pre-intervention muscular performance characteristics by group and corresponding raw change values (in parentheses) post-intervention. Inter-group p-value indicates the difference between change scores.

	Control (n = 7)	Experimental (n = 7)	Inter-group p-value
Smith 1RM Bench Pull, kg	92.8 ± 15.2	98.2 ± 14.6	0.241
	(5.2 ± 4.1)*	(2.6 ± 3.6)	
Velocity (maximum), m/s	1.39 ± 0.13	1.33 ± 0.14	0.004
	(-0.01 ± 0.08)	(0.12 ± 0.04)*	
Velocity (at Pmax), m/s	0.73 ± 0.06	0.71 ± 0.07	0.067
	(-0.02 ± 0.05)	(0.04 ± 0.07)	
Velocity (at 1RM), m/s	0.52 ± 0.04	0.48 ± 0.04	0.074
	(0.00 ± 0.04)	(0.04 ± 0.04)*	
Force (max; 1RM), N	908.6 ± 148.9	964.0 ± 143.7	0.196
	(52.2 ± 40.2)*	(24.8 ± 34.4)	
Force (Pmax), N	702.2 ± 149.1	730.9 ± 113.7	0.127
	(45.9 ± 42.8)*	(14.6 ± 24.7)	
Time: Peak Force (max), s	0.10 ± 0.02	0.09 ± 0.02	0.075
	(0.01 ± 0.02)	(-0.01 ± 0.02)	
Time: Peak Force (Pmax), s	0.15 ± 0.04	0.13 ± 0.02	0.152
	(0.04 ± 0.05)	(-0.01 ± 0.07)	
Time: Peak Force (1RM), s	0.20 ± 0.07	0.17 ± 0.06	0.441
	(-0.01 ± 0.06)	(-0.04 ± 0.06)	
Pmax load, %1RM	77.4 ± 3.0	75.7 ± 2.3	0.698
	(3.7 ± 6.9)	(5.7 ± 10.6)	
Power (max), W	511.0 ± 99.6	516.7 ± 100.2	0.155
	(21.4 ± 26.4)	(44.7 ± 30.8)*	
Power (1RM), W	474.2 ± 105.9	462.2 ± 97.2	0.246
	(26.1 ± 40.6)	(54.2 ± 45.2)*	

*Indicates within group change following intervention significant at $p<0.05$

Alteration of muscular performance characteristics

Strength-power variables measured and their observed changes following the training intervention period are displayed in Table 17. Significant changes were seen in the control group for 1RM (5.2 ± 4.0%; p = 0.016) and maximum force able to be produced at 1RM (5.4 ± 4.0%; p = 0.014). The experimental group showed significant changes in maximum velocity (8.4 ± 2.6%; p = 0.0002), maximum power (7.8 ± 4.9%; p = 0.009), and power produced at the 1RM load (10.3 ± 8.9%; p = 0.019). Only maximal velocity (greater increase for the experimental group) met the pre-defined α level for significant difference between the groups, however there was a noticeable pattern that the control group appeared to improve more in the force and maximal strength measures while the experimental group appeared to improve more in the velocity, time to peak force and power variables.

Changes in grinding performance

Both groups exhibited improvements in grinding performance following the intervention period (see Table 18). The differences in performance changes between groups were not statistically significant; however, the improvements were greater for the experimental group than the control group in both the moderate and heavy load grinding conditions. The likelihood of a performance benefit from the experimental training was greater as the grinding load increased (See Table 17). The likelihood of a trivial effect was high, particularly for moderate load grinding, and the probability of a negative effect was very low.

Table 18: Percent changes in moderate and heavy load grinding performance following the intervention period, with associated p-values. Difference between control and experimental groups (with 90% confidence limits) and the probabilities of a real effect from the experimental training are presented.

	Moderate load (n = 7)	Heavy load (n = 4)
Control group	4.1 ± 2.2% (p = 0.002)	10.4 ± 4.5% (p = 0.019)
Experimental group	5.9 ± 1.9% (p = 0.0002)	16.3 ± 8.6% (p = 0.061)
Inter-group difference	1.8% (90% CL ± 2.1)	6.0% (90% CL ± 12.4)
Likelihood of positive effect	22%	52%
Likelihood of trivial effect	78%	42%
Likelihood of negative effect	0%	5%

Determinants of performance changes

Correlational analysis showed that changes in power production (maximum or at 1RM) had moderate to large correlations with changes in moderate load grinding performance, indicating an explained variance of approximately 35% (R^2 = 0.35-0.38) of the pre-post change seen across the group (see Table 19). For heavy load grinding performance, changes in time to peak force at 1RM had a very large correlation with change in grinding performance, with approximately 70% shared variance. Improvements in maximum power capability also demonstrated a positive relationship with changes in performance, although the low statistical power means that the exact nature of this relationship is unclear, with confidence limits indicating the true correlation could be anywhere from 0.1 (small) to 0.9 (nearly perfect).

Table 19: Correlations (R>0.5) between changes in backward grinding performance at two loads and changes in muscular performance variables.

Grinding load	Variable	R	90% C.L.	*p-value*
Moderate	Power (1RM)	0.61	±0.31	0.019
	Power (max)	0.59	±0.32	0.027
Heavy	Time: Peak Force (1RM)	-0.89	±0.19	0.003
	Power (max)	0.56	±0.49	0.150

DISCUSSION

Backward grinding performance has been more strongly associated with muscular power compared to muscular strength for forward grinding [35]. As such, the aim of this study was to determine whether the influence of strength training on backward grinding performance could be improved by altering pull based resistance training exercises to better stimulate the muscular performance characteristics associated with the performance in question. Key questions included: 1) Was the experimental training alteration successful in changing muscular performance characteristics in the manner desired? 2) Did the experimental intervention prove advantageous to performance? 3) Were the muscular performance characteristics identified actually linked to changes in performance?

Prior to answering these questions however, it is necessary to examine how effective the intervention was in affecting a different stimulus between the two groups. Training data were collected during the final two weeks of the intervention period, at a point were loading was highest and therefore differences in lift tempo between the two groups were theoretically likely to be smallest. While concentric velocity for the experimental group was significantly faster during the first heavy work set, it was notable that there was a substantially longer lift time and decreased velocity in the second heavy work set while the control group remained relatively consistent for the two sets. Although the experimental group was still lifting faster in the second heavy work set, the difference between the two groups was only marginal. One possible explanation for this drop-off in speed for the second set is that the sailors in the experimental group were still adapting to the faster tempo lifting technique and as such tended to revert back to their normal/natural training speed under fatigue – a theory at least partially supported by the consistency of the control group. However, a major limitation in the interpretation of this training data is that there were no pre-intervention data to give a comparative baseline. It is therefore not possible to determine for certain whether the observations from the training data are a product of the different instructions given regarding training speed to the two groups, or simply a function of different natural training tempos between the sailors in the two groups. Therefore, while the evidence does tend to suggest that the intervention was successful in producing a kinematically different training stimulus for the two groups, the possibility of this occurring through coincidence must still be acknowledged.

Alteration of muscular performance characteristics

When examining changes in muscular performance characteristics displayed by the two groups following the training intervention it appears that the different training methods were successful in altering muscular performance characteristics in accordance with their intent. While there was only one variable that showed significantly different changes between the two training groups (maximal velocity capability improving more in the experimental group), there were a number of measures where the inter-group change difference was not much over the $p = 0.05$ threshold for significance and there was a definite trend in the direction of the differences. Velocity and power production values consistently increased and time to peak force decreased more so in the experimental group while force capability changes were greater in the control group. These results were consistent with the training stimuli used in each group, with the experimental group typically generating greater speed and power during lifts. While these results were not completely conclusive, they do indicate that the experimental training intervention seems better suited to improving power and speed-strength capability more so than the conventional tempo training. However, all participants in this study had substantial training experience, a factor which has been shown to augment the development of power [89].

Changes in grinding performance

With respect to the main parameter of interest from a sport performance viewpoint, both groups exhibited significant improvements in backward grinding performance following the intervention period. In terms of a carry over effect from the different muscular performance changes produced by the different training interventions, there was a non-significant performance benefit in work output for the experimental group in both moderate (1.8%, $p = 0.235$) and heavy (6.0%, $p = 0.474$) load grinding. Due to the low subject numbers in this study a non-traditional method [88], devised with low subject numbers and sporting performance in mind, was therefore used to derive the probability of benefit or harm (in a performance sense) from the experimental intervention. This analysis indicated that for moderate load grinding the likelihood of the experimental training having a trivial effect on performance was very probable (78%), while there was a small chance of a positive effect (22%), and it would almost certainly not have a negative effect (0%). In comparison, for heavy load grinding there was a possibility of either a positive effect (52%) or a trivial effect (42%), while still being unlikely to produce a negative effect (5%). While there is uncertainty over the positive benefit of the experimental training, there is very little chance of a negative effect on performance from this training method. Based on this assessment, employing the experimental training method on a permanent basis could safely be recommended as an option with the potential to improve backward grinding performance, in particular at heavy loads, while being low risk in terms of any potential performance impairment.

There were a number of limitations to this study and the effects observed here would most probably have been further clearer with a few methodological changes:

- While the results of this study, along previous research evidence indicates that neural focussed power development training can be effective in relatively short periods (5-8 weeks) [60, 90], a longer training intervention period would typically magnify any results.
- Greater subject numbers are likely to produce more definitive results.
- There is the possibility that results could have been improved by a more disparate training stimulus for the two groups than we were practically limited to in this situation.

Determinants of performance changes

Although the effect on performance is the key result of the study, it is also useful for our understanding to try and determine what mechanisms were responsible for the observed performance changes. Because the numbers of participants in this study were lower than what would be ideal, correlations have to be interpreted with caution (reflected by confidence limits), however, they do provide an indication of the mechanistic variables most linked to performance change. The variables identified as having the greatest relationship to changes in grinding performance, were power and rate of force development. These results provide support to the proposed benefits of the velocity-focussed explosive training as the variables identified as having the greatest influence on changing grinding performance were all found to improve more in the experimental group.

Of particular note was the very strong relationship between time to peak force and heavy load grinding performance, which was substantially stronger than any of the correlations for moderate load grinding performance. Although the total number of sailors who completed the moderate load condition was higher (n=14 versus n=8 for heavy load), it may be that, with only the stronger and more accomplished grinders completing the heavy load condition, the within-sailor performance was more consistent and therefore responses were more uniform and more predictable. It may also be due to the stronger relationship between grinding performance and strength as grinding load increases, resulting in better predictive abilities of muscular performance characteristics.

CONCLUSIONS

Although participant limitations of the study will have impacted on the ability to obtain a clear and conclusive picture of what effect the speed-focussed strength training may have on grinding performance, our findings enable us to suggest the following:

- There is reasonable evidence that the experimental training intervention was successful in stimulating different changes in the muscular performance characteristics of Emirates Team New Zealand sailors. Speed-focussed training of pull-based exercises was more successful than conventional training for improving the ability of sailors to produce higher power outputs and velocities in the bench pull movement.
- Speed-focussed training resulted in a notably, but not statistically significantly, greater improvement in backward grinding performance than conventional training, over the six-week period. While the evidence of a positive benefit from this training method is not incontrovertible, there appears to be no evidence of a negative effect.

- The muscular performance characteristics that show the greatest relationship with changes in backward grinding performance were entirely those better stimulated by the experimental training intervention (power output, time to maximum force, velocity). The predictive ability of power/speed-strength variables increased with increasing grinding load.

Based on the combination of evidence it seems reasonable to encourage the use of the speed-focussed weight training methods for pull-based exercises to be employed for America's Cup sailors involved with grinding. The likelihood of a detrimental effect is extremely low, and the evidence for a beneficial effect is encouraging.

CHAPTER 8

DISCUSSION/CONCLUSIONS

Grinding is a key element of sailing performance in the America's Cup – the oldest and most prestigious competition in world yachting. Historically there has been little published scientific research on America's Cup yachting in general and the grinding movement specifically. While there have been a number of new papers on this topic during the period in which the research making up this thesis was conducted, to date no published study has examined the biomechanics of technique and musculo-skeletal performance in relation to grinding performance. A greater understanding could help to improve/optimise grinding technique and/or land-based training methods to advance performance. This research therefore aimed to analyse the grinding movement and factors relating to grinding performance. Specifically the series of studies in this doctoral thesis aimed to: (1) provide a detailed description of the biomechanics of the grinding motion; (2) determine what elements of grinding technique and muscular performance characteristics related to grinding performance; and (3) evaluate the effects of a training intervention (determined by previous findings) on grinding performance.

Grinding performance reliability

The reliability of grinding performance was examined (Chapter 2) to determine levels of tolerance for identifying performance differences between individuals and performance changes over time. Although grinding direction (forward or backward) did not influence reliability, performance consistency was affected to a small degree by the performance variable used (peak power, SEM = 1.3-5.4%; work over five seconds, SEM = 1.6-3.9%) and system resistance (light, SEM = 1.6-2.6%; moderate, SEM = 3.9-3.5%; heavy, SEM = 3.7%), and to a greater degree by platform orientation (flat, anterior-posterior tilt, lateral tilt, SEM = 4.6-6.9%). Work performed (or average power) over five seconds was a more robust measure of performance than peak power in terms of percent variation, a finding consistent with a meta-analysis [6] on reliability in performance tests showing that variation decreased with increasing time up to 1 minute. However, work performed and peak power both exhibited very high correlational agreement in a test-retest situation indicating that relative performance/differentiation between individuals was achieved consistently - a factor crucial for descriptive studies, as employed mostly in this research. As a result of this finding, work over five seconds rather than peak power was used as the primary measure of performance throughout this research.

In terms of the effect of load/resistance, performance reliability decreased with increasing resistance (exercise intensity). From a pure reliability perspective it would therefore be most prudent to test performance at light loads, however, in terms of maintaining the validity of the testing it was necessary to examine performance across a range of loads in order to sufficiently address the on-water performance environment. An additional factor in the use of different system resistances was that high resistance/heavy load grinding performance is generally regarded as more important to on-water performance. The observed reliability of grinding performance at different loads was not used to determine ideal test protocols, but rather to ascertain the magnitude of changes likely to be required in an intervention setting in order to be confident of a real effect. For both moderate and heavy load grinding (which were of most interest) a performance change of over 4%, for either forward or backward grinding, was considered to be interpreted with confidence.

Platform orientation was the final factor examined, and the one that displayed the greatest influence on performance reliability. Grinding on a tilted platform (simulating boat heel) was less reliable than grinding on the flat and, within the tilt conditions, performance on a lateral tilt was more variable (SEM = 5.8-6.9%) than on an anterior-posterior tilt (SEM = 4.7-5.9%). Consequently, grinding performance throughout this research was assessed in flat conditions, with the exception of the study in Chapter 3 that looked specifically at the effects of tilt direction on performance.

Grinding technique

The study addressing the influence of tilt direction on grinding performance (Chapter 3) was directly related to a deck layout/design question by the Emirates Team New Zealand syndicate who were weighing up the possibility of altering the orientation of the primary grinding pedestals (the two pedestals nearest the front of the yacht). The “conventional” primary pedestal orientation – where the sailors face along the boat and are subjected to lateral tilt when the boat was heeling, was compared with an “in-line” orientation option, in which sailors would face across the boat and be subjected to anterior-posterior tilt. During individual testing there was little performance difference overall between the two orientations, although there was an indication that the conventional system was advantageous when grinding against less resistance (2.0%, p = 0.017), compared to a small benefit from the in-line system at heavier loads (1.0%, p = 0.254). However, the results in paired grinding (two sailors, one on either side of the pedestal grinding together) where much more conclusive, with a significant performance benefit to the in-line system (+8.0%, p<0.001).

Findings from the study examining the kinematics, muscle activation patterns and torque application in forward and backward grinding (Chapter 4) provide some indication on why, in paired grinding, an anterior-posterior tilt was so much more advantageous than a lateral tilt when there was minimal difference in individual grinding. Torque application traces showed that both forward and backward grinding demonstrate sections of particularly low torque during the cycle or “dead spots”. In a situation where the paired sailors, grinding in opposite directions, are essentially level with each other (in flat conditions or lateral heel), these dead spots occur in close proximity to each other, which will result in inefficiency due to the deceleration and subsequent re-acceleration of the handles. In comparison, an anterior-posterior tilt changes the effective height of the pedestal because of the sailors position (above or below the pedestal) and will therefore alter the primary line of motion, which occurs in the push phase for forward grinding and the pull phase for backward grinding. This would result in a relative shift of the positions of the dead spots and create a smoothing effect, allowing more consistent handle speed throughout the rotation and making for a more efficient grinding cycle. Although there was good evidence of a performance advantage when grinding with the in-line orientation, the information required in making decisions on boat design and deck layout is multi-factorial and some of the additional factors outweighed the observed benefits from this study and the syndicate maintained a conventional layout.

Although both backward and forward grinding shared torque dead spots, overall the biomechanics of these two movements were notably different, as outlined in Chapter 4. The greatest amount of work on the handles (peak torque) occurred in forward grinding as the handles were on the downward section of the rotation, corresponding with the upper body push phase (shoulder flexion, elbow extension) and a period of high activation of the pectoralis major, anterior deltoid and triceps brachii muscles. In contrast, the upper body pull (shoulder extension, elbow flexion – latissimus dorsi, posterior deltoid, biceps brachii) was the primary motion for torque generation in backward grinding, with peak torque occurring across the top of the handles rotation. During forward grinding there was a greater spread of active muscles throughout the rotation than in backward grinding. This contributed to a greater maintenance of torque during forward grinding, with relatively high levels (>50 N m) observed through 260° of the rotation, compared to torque of over 50 N m for only 170° of the rotation during backward grinding. This puts additional focus on the upper body pull movement in grinding performance overall, as in forward grinding the dominant push phase is complimented by a weaker but still notable pull phase across the lower section of the rotation, but in backward grinding the pull phase was responsible for the vast majority of the work performed, with work through the lower half of the cycle (where a push phase would theoretically occur) virtually non-existent.

Muscular performance

Prior to this research there was a substantial body of research on the effect of load on muscular performance characteristics in the upper body push movement but very little examining the upper body pull movement and none conducting a direct comparison between the two movements in the same population or the importance of force, velocity and power for grinding performance. Our examination of the bench press (upper body push) and bench pull (upper body pull) in the strength-trained sailors (Chapter 5) demonstrated the substantially different muscular performance characteristics of these two movements. Differences in muscle architecture mean that, at the same relative load, higher force values are generated in the bench press but higher velocity and power values occur in the bench pull. Power was maximised at a significantly higher relatively load for the bench pull (79% 1RM) than the bench press (53% 1RM). This finding in itself has potentially wider implications in the area of conditioning generally, not just in sailing.

Muscular capability was then related to grinding performance (Chapter 6). Maximum force generating capability correlated very highly ($r > 0.87$) with both forward and backward grinding, however, maximum power had just as strong a relationship as force to backward grinding performance, although only a moderate relationship with forward grinding. This finding was of interest as Emirates Team New Zealand had previously trained both the push and pull movements primarily for maximal strength/force generating capability. The apparently high importance of power in backward grinding performance raised the possibility that an adaptation of the current training protocols to place greater emphasis on the speed component of strength could provide an additional stimulus to improve backward grinding performance.

Training intervention

Based on the findings outlined in Chapter 6, a six-week resistance training intervention was implemented. The aim was to improve backward grinding performance through increased muscular power in the upper body pull movement (Chapter 7). The experimental group, who performed speed-focussed pull exercises, demonstrated greater improvements in power, velocity and time to maximum force variables while the control group (slow, controlled tempo) improved more in maximal strength and force variables. This indicates that a relatively minor adjustment in training protocol (increased lift speed, with little if any change in load lifted) can induce different adaptations in muscular function. There was a greater mean grinding performance increase in the experimental group than the control group, however there was considerable variation within the groups, a finding consistent with individual responses. Importantly, the evidence suggested that while a positive benefit from the training intervention on performance was not conclusive, there was little likelihood of the experimental training method being detrimental to performance. This made the method used attractive as a low risk option with potential gains. In terms of mechanisms for the performance improvements, increased power and decreased time to peak force were the variables which explained the greatest amount of the observed performance changes.

Thesis limitations

The studies presented in this thesis were at times limited by methodological constraints. Throughout the research we have used a grinding ergometer for the assessment of grinding performance due to the difficulties of conducting this type of research on board an America's Cup Class yacht in an on-water setting. The design of the ergometer and feedback from the participating sailors supported the premise that it provided a realistic simulation of on-water grinding, however it must be acknowledged that there may be differences.

A second general limitation was that the availability of individual sailors at any given time and the nature of some of the testing (relative to sailor ability) meant that the number of participants in each study, and the different sections within each study, varied greatly (n = 6-18). As a result, participant numbers were generally lower than would be ideal, although this is not uncommon in studies involving elite populations. Sample size could have been increased by using un-skilled participants, however, the results obtained from novice performers will typically vary greatly from elite athletes and as such would not have added to the primary aim of the thesis: understanding and improving performance at the elite, America's Cup level.

In Chapter 3 the influence of tilt on grinding performance was only examined at static heel angles due to the limitations of the ergometer. In reality the majority of grinding work when sailing upwind (where heel is involved) is performed as the boat rolls through a tack, meaning it transfers from heeling in one direction to heeling in the other direction. Ideally the simulator would have been capable of dynamic motion to fully explore this dynamic. Secondly, the inclusion of some of the techniques employed in Chapter 4 to examine the function of the sailors would have enabled better interpretation of the differences observed, however this was not possible given the constraints placed on conducting this particular study.

When examining the biomechanical characteristics of grinding in Chapter 4, kinematics, muscle activation patterns and torque application were measured on only one side of the body due to equipment restrictions. A three-dimensional, bilateral analysis would have provided additional information on additional factors of non-sagittal body motion and whether there were biases in the function of dominant and non-dominant limbs.

In Chapter 7 it would have been beneficial to monitor the training speeds of all of the sailors involved prior to the commencement of the training intervention. While it was observed that the experimental (speed-focussed) training group had faster lift speeds than the control group during the intervention, it is not known whether this was entirely the result of the intervention instructions as it is likely that some individuals have faster “natural” lifting speeds than others. In addition, a possibility that was not considered until after the completion of this study was that given that the pull motion is also utilised in the lower section of the forward grinding cycle (albeit, secondary to the push movement), the intervention may have also yielded performance gains in forward grinding. Unfortunately this could not be ascertained as forward grinding was not assessed as part of this study.

Future directions

This thesis reported reliability statistics for grinding performance on an ergometer and described the biomechanical and muscular performance characteristics of America’s Cup sailors and the relationships of these characteristics to grinding performance. Based on these analyses a resistance-training intervention was implemented to increase muscular power output in the upper body pull movement, which resulted in an improvement in backward grinding performance. Further studies are recommended as follows:

- A three-dimensional, bi-lateral analysis of grinding technique. This research will ascertain whether there are additional movements outside of the sagittal plane (e.g. trunk rotation), which are key to grinding performance, specific contributions from individual joints, and the presence of any bi-lateral variation.

- What is the effect of a technique intervention on performance? There is some evidence from this study that consistency of torque application throughout the rotation is beneficial for forward grinding performance, but emphasis on purely the pull phase across the top half of the rotation benefits backward grinding performance. An intervention focussing on developing these attributes could determine whether this is a positive strategy.

- This thesis has provided some evidence that developing muscular power and rate of force development can improve grinding performance. However, findings were not completely conclusive and as such this needs to be investigated further – examining the most efficient ways of developing these muscular characteristics and re-visiting the transfer of improvements in these variables to grinding performance.

- An analysis of kinematic and kinetic similarities or differences between grinding on a land-based ergometer and on-water, with the influence of a semi-unstable platform.

Conclusions

The most reliable grinding performance measure was work performed over five seconds on a flat platform and against a light load. Grinding performance was negatively affected by deck heel, with anterior-posterior heel (relative to the sailor orientation) less detrimental than lateral heel. In terms of the effect of load/resistance, performance reliability decreased with increasing resistance (exercise intensity). During paired grinding (two sailors, one on either side of the pedestal grinding together) tilt in the anterior-posterior direction (in-line system) had a significant performance benefit (8%) over lateral tilt (conventional system). Muscle activation and kinematics were substantially different between forward and backward grinding, with forward grinding displaying a greater distribution of active muscles, and consequently torque application, throughout the rotation. Key physical conditioning training movements in relation to maximal torque application were the upper body push for forward grinding and upper body pull for backward grinding. Within these movements, force generating capability in the push had the greatest relationship with forward grinding performance while power in the pull explained the greatest amount of the variation observed in backward grinding performance. A speed-focussed resistance training intervention of six weeks to enhance power capability in the upper body pull movement produced promising improvements in backward grinding performance. The speed-focussed training group had greater power, velocity and rate of force development and greater changes in backward grinding performance at both moderate (+1.8%) and heavy (+6.0%) load than the control group. In terms of determinants of performance change, maximum power output and power at 1RM had large correlations ($r = 0.56$-0.61) with changes in both moderate and heavy load grinding performance. However, time to peak force had the strongest single relationship across either load, explaining 70% of the change in heavy load grinding performance. These findings confirm key variables relating to performance that could be targeted in conditioning practice. To improve/optimise grinding technique we suggest a focus on upper body pull movements. As power was maximised at a significantly higher relatively load for the bench pull than the bench press land-based training methods should focus on bench pull exercises to advance performance. There should also be emphasis on the speed component of strength training to provide an additional stimulus to improve backward grinding performance.

This research has contributed knowledge regarding the understanding of biomechanical factors involved in the performance of grinding. A detailed description of the muscle activation patterns, joint actions and movement, muscular performance characteristics and how they combine to generate the applied torque which defines performance has been provided, allowing a better understanding of how performance can potentially be improved. In addition, this research has evaluated an alternative training methodology that has been shown to be an effective way to improve power and speed in the upper body pull movement, in addition to having specific positive effects on grinding performance. Further investigations into some of the other factors identified in this research as being related to performance may yield additional avenues for improvement.

REFERENCES

1.Neville V, Pain MT, Folland JP. Aerobic power and peak power of elite America's Cup sailors. European Journal of Applied Physiology. 2009 Feb 21;106(1):149-57.

2.Bernardi E, Fontana G, Delussu AS, Quattrini FM, Bernardi M, Madaffari A. Nutritional requirements for an America's Cup crew. In: Legg SJ, Mackie H, Cochrane D, editors. Human Performance in Sailing Conference; 2003; Auckland, New Zealand: Unitec and Massey University; 2003. p. 31-5.

3.Bernardi M, Fontana G, Rodio A, Madaffari A, Brugnoli M, Marchetti M. Physiological characteristics of America's Cup sailors. In: Legg SJ, Mackie H, Cochrane D, editors. Human Performance in Sailing Conference; 2003; Auckland, New Zealand: Unitec and Massey University; 2003.

4.Pearson SN, Hume PA, Mellow P, Slyfield D. Anthropometric dimensions of Team New Zealand America's Cup sailors. New Zealand Journal of Sports Medicine. 2005;33(2):52-7.

5.Pearson SN. Power output of America's Cup grinders can be improved with a biomechanical technique intervention [Master of Science]. Auckland: Auckland University of Technology; 2003.

6.Hopkins W, Schabort EJ, Hawley JA. Reliability of power in physical performance tests. Sports Medicine. 2001;31(3):211-34.

7.Norton K, Olds T, editors. Anthropometrica : A textbook of body measurement for sports and health courses. Sydney: University of New South Wales Press; 1996.

8.Sloan AW, Weir JB. Nomograms for prediction of body density and total body fat from skinfold measurements. Journal of Applied Physiology. 1970 Feb;28(2):221-2.

9.Hopkins WG. Reliability from consecutive pairs of trials. A new view of statistics. sportsci.org: Internet Society for Sport Science, sportsci.org/resource/stats/xrely.xls; 2000.

10.Schabort EJ, Hawley JA, Hopkins WG, Blum H. High reliability of performance of well-trained rowers on a rowing ergometer. Journal of Sports Sciences. 1999 Aug;17(8):627-32.

11.Bennell K, Crossley K, Wrigley T, Nitschke J. Test-retest reliability of selected ground reaction force parameters and their symmetry during running. Journal of Applied Biomechanics. 1999;15:330-6.

12.Cooke WH, Whitacre CA, Barnes WS. Measuring fatigue relative to peak power output during high-intensity cycle sprinting. Research Quarterly for Exercise and Sport. 1997 Dec;68(4):303-8.

13.Williams JH, Barnes WS, Signorile JF. A constant-load ergometer for measuring peak power output and fatigue. Journal of Applied Physiology. 1988 Nov;65(5):2343-8.

14.Grooten WJ, Puttemans V, Larsson RJ. Reliability of isokinetic supine bench press in healthy women using the Ariel Computerized Exercise System. Scandinavian Journal of Medicine and Science in Sports. 2002 Aug;12(4):218-22.

15.Callaghan MJ, McCarthy CJ, Al-Omar A, Oldham JA. The reproducibility of multi-joint isokinetic and isometric assessments in a healthy and patient population. Clinical Biomechanics. 2000 Nov;15(9):678-83.

16.Morrow JR, Jr., Jackson AW. How "significant" is your reliability? Research Quarterly for Exercise and Sport. 1993 Sep;64(3):352-5.

17.Madsen OR. Torque, total work, power, torque acceleration energy and acceleration time assessed on a dynamometer: reliability of knee and elbow extensor and flexor strength measurements. European Journal of Applied Physiology and Occupational Physiology. 1996;74(3):206-10.

18.Whiting P. The 32nd America's Cup: A simple guide. Chichester: John Wiley & Sons; 2007.

19.Neville V, Calefato J, Perez-Encinas C, Rodilla-Sala E, Rada-Ruiz S, Dorochenko P, et al. America’s Cup yacht racing: Race analysis and physical characteristics of the athletes. Journal of Sports Sciences. 2009;27(9):915-23.

20.Bressel E, Heise GD. Effect of arm cranking direction on EMG, kinematic, and oxygen consumption responses. Journal of Applied Biomechanics. 2004;20:129-43.

21.Fujii N, Nagasaki H. Efficiency and proficiency of bimanual cranking: differences between two cranking patterns. Perceptual and Motor Skills. 1995 Feb;80(1):275-83.

22.Pearson SN, Hume PA, Slyfield D, Cronin JB. External work and peak power are reliable measures of ergometer grinding performance when tested under load, deck heel and grinding direction conditions. Sports Biomechanics. 2007;6(1):71-80.

23.Lewis SF, Taylor WF, Graham RM, Pettinger WA, Schutte JE, Blomqvist CG. Cardiovascular responses to exercise as functions of absolute and relative work load. Journal of Applied Physiology. 1983 May;54(5):1314-23.

24.Karn R. Personal communication regarding OneWorld testing of the effect of deck heel on grinding performance. 2008.

25.Pearson SN, Hume PA, Cronin JB, Slyfield D. Biomechanical characteristics of grinding in America's Cup sailing. In: Harrison AJ, Anderson R, Kenny I, editors. 27th International Symposium on Biomechanics in Sports; 2009 August 17-21; Limerick, Ireland: Faculty of Education & Health Sciences, University of Limerick; 2009. p. 694.

26.Hopkins WG. Analysis of a post-only crossover trial (Excel spreadsheet). A new view of statistics. newstats.org/xPostOnlyCrossover.xls; 2006.

27.Pearson SN, Hume PA, Ackland T, Slyfield D. America's Cup grinders power output can be improved with a biomechanical technique intervention. In: Wang Q, editor. XXIII International Symposium on Biomechanics in Sports; 2005 August 22-27; Beijing, China: The China Institute of Sport Science; 2005. p. 309-12.

28.Rayner R, Thompson T. The Story of the America's Cup 1851-1995. Toronto, Canada: Warwick Publishing; 1996.

29.Bernardi M, Quattrini FM, Rodio A, Fontana G, Madaffari A, Brugnoli M, et al. Physiological characteristics of America's Cup sailors. Journal of sports sciences. 2007 Aug;25(10):1141-52.

30.Allen JB. Sports medicine injuries in the America's Cup 2000. New Zealand Journal of Sports Medicine. 2005;33(2):43-7.

31.Hadala M, Barrios C. Different strategies for sports injury prevention in an America's Cup yachting crew. Medicine and science in sports and exercise. 2009 Aug;41(8):1587-96.

32.Hadala M, Barrios C. Sports injuries in an America's Cup yachting crew: A 4-year epidemiological study covering the 2007 challenge. Journal of Sports Sciences. 2009 May;27(7):711-7.

33.Neville V, Molloy J, Brooks JH, Speedy DB, Atkinson G. Epidemiology of injuries and illnesses in America's Cup yacht racing. British Journal of Sports Medicine. 2006 Apr;40(4):304-11.

34.Allen JB, De Jong MR. Sailing and sports medicine: a literature review. British Journal of Sports Medicine. 2006 Jul;40(7):587-93.

35.Pearson SN, Cronin JB, Hume PA, Slyfield D. Strength and power determinants of grinding performance in America's Cup sailors. Journal of Strength and Conditioning Research. 2009;23(6):1883-9.

36.Bernardi E, Delussu SA, Quattrini FM, Rodio A, Bernardi M. Energy balance and dietary habits of America's Cup sailors. Journal of Sports Sciences. 2007 Aug;25(10):1153-60.

37.Neville V, Gant N, Folland JP. Thermoregulatory demands of Elite Professional America's Cup Yacht Racing. Scandinavian Journal of Medicine and Science in Sports. 2009 Jun 23;In press, doi: 10.1111/j.1600-0838.2009.00952.x.

38.Bressel E, Bressel M, Marquez M, Heise GD. The effect of handgrip position on upper extremity neuromuscular responses to arm cranking exercise. Journal of Electromyography and Kinesiology. 2001 Aug;11(4):291-8.

39.Cummins TD, Gladden LB. Responses to submaximal and maximal arm cycling above, at, and below heart level. Medicine and science in sports and exercise. 1983;15(4):295-8.

40.Sawka MN. Physiology of upper body exercise. Exercise and Sport Sciences Reviews. 1986;14:175-211.

41.Mayhew JL, Prinster JL, Ware JS, Zimmer DL, Arabas JR, Bemben MG. Muscular endurance repetitions to predict bench press strength in men of different training levels. Journal of Sports Medicine and Physical Fitness. 1995 Jun;35(2):108-13.

42.Basmajian JV, Blumenstein R. Electrode placement in EMG biofeedback. Baltimore: Williams & Wilkins; 1980.

43.Hodges PW, Bui BH. A comparison of computer-based methods for the determination of onset of muscle contraction using electromyography. Electroencephalography and Clinical Neurophysiology. 1996 Dec;101(6):511-9.

44.Walter CB. Temporal quantification of electromyography with reference to motor control research. Human Movement Science. 1984;3:155-62.

45.Hopkins WG. Calculating likely (confidence) limits and likelihoods for true values (Excel spreadsheet). A new view of statistics. sportsci.org: Internet Society for Sport Science, sportsci.org/resource/stats/xcl.xls; 2002.

46.Cohen J. Statistical power analysis for the behavioral sciences. 2nd ed. New Jersey: Lawrence Erlbaum; 1988.

47.Bertucci W, Grappe F, Girard A, Betik A, Rouillon JD. Effects on the crank torque profile when changing pedalling cadence in level ground and uphill road cycling. Journal of Biomechanics. 2005 May;38(5):1003-10.

48.Neptune RR, Hull ML. Evaluation of performance criteria for simulation of submaximal steady-state cycling using a forward dynamic model. Journal of Biomechanical Engineering. 1998 Jun;120(3):334-41.

49.Reiser RF, Peterson ML, Broker JP. Instrumented bicycle pedals for dynamic measurement of propulsive cycling loads. Sports Engineering. 2003;6(1):41-8.

50.Neptune RR, Kautz SA, Zajac FE. Muscle contributions to specific biomechanical functions do not change in forward versus backward pedaling. Journal of biomechanics. 2000 Feb;33(2):155-64.

51.Pearson SN, Cronin JB, Hume PA, Slyfield D. Effects of a power-focussed resistance training intervention on backward grinding performance in America's Cup sailing. Sports Biomechanics. in press.

52.Hamill J, Knutzen KM. Biomechanical Basis of Human Movement. USA: Williams & Wilkins; 1995.

53.Harman E. Strength and power: A definition of terms. National Strength and Conditioning Association Journal. 1993;15(6):18-20.

54.Abernethy P, Wilson G, Logan P. Strength and power assessment. Issues, controversies and challenges. Sports Medicine. 1995 Jun;19(6):401-17.

55.Sale DG. Testing strength and power. In: MacDougall JD, Wenger HA, Green HJ, editors. Physiological Testing of the High-Performance Athlete. Champaign, IL: Human Kinetics; 1991. p. 21-106.

56.Lyttle AD, Wilson GJ, Ostrowski KJ. Enhancing performance: maximal power versus combined weights and plyometrics training. Journal of Strength and Conditioning Research. 1996;10(3):173-9.

57.Pearson D, Faigenbaum A, Conley M, Kraemer WJ. The National Strength and Conditioning Association's basic guidelines for the resistance training of athletes. Strength and Conditioning Journal. 2000;22(4):14-27.

58.Cronin J, McNair PJ, Marshall RN. Developing explosive power: a comparison of technique and training. Journal of Science and Medicine in Sport. 2001 Mar;4(1):59-70.

59.Cronin J, Sleivert G. Challenges in understanding the influence of maximal power training on improving athletic performance. Sports Medicine. 2005;35(3):213-34.

60.Wilson GJ, Newton RU, Murphy AJ, Humphries BJ. The optimal training load for the development of dynamic athletic performance. Medicine and Science in Sports and Exercise. 1993 Nov;25(11):1279-86.

61.McBride JM, Triplett-McBride T, Davie A, Newton RU. The effect of heavy- vs. light-load jump squats on the development of strength, power, and speed. Journal of Strength and Conditioning Research. 2002 Feb;16(1):75-82.

62.Harris NK, Cronin JB, Hopkins WG. Power outputs of a machine squat-jump across a spectrum of loads. Journal of Strength and Conditioning Research. 2007 Nov;21(4):1260-4.

63.Cronin JB, Jones JV, Hagstrom JT. Kinematics and kinetics of the seated row and implications for conditioning. Journal of Strength and Conditioning Research. 2007 Nov;21(4):1265-70.

64.Kramer JF, Morrow A, Leger A. Changes in rowing ergometer, weight lifting, vertical jump and isokinetic performance in response to standard and standard plus plyometric training programs. International Journal of Sports Medicine. 1993;14(8):449-54.

65.Liow DK, Hopkins WG. Velocity specificity of weight training for kayak sprint performance. Medicine and Science in Sports and Exercise. 2003 Jul;35(7):1232-7.

66.Sharp MA, Harman E, Vogel JA, Knapik JJ, Legg SJ. Maximal aerobic capacity for repetitive lifting: comparison with three standard exercise testing modes. European Journal of Applied Physiology and Occupational Physiology. 1988;57(6):753-60.

67.Kawamori N, Crum AJ, Blumert PA, Kulik JR, Childers JT, Wood JA, et al. Influence of different relative intensities on power output during the hang power clean: identification of the optimal load. Journal of strength and conditioning research / National Strength & Conditioning Association. 2005 Aug;19(3):698-708.

68.Chiu LZF, Schilling BK, Fry AC, Weiss LW. Measurement of resistance exercise force expression. Journal of Applied Biomechanics. 2004;20:204-12.

69.Cronin JB, Hing RD, McNair PJ. Reliability and validity of a linear position transducer for measuring jump performance. Journal of Strength and Conditioning Research. 2004 Aug;18(3):590-3.

70.Lieber RL, Friden J. Functional and clinical significance of skeletal muscle architecture. Muscle and Nerve. 2000 Nov;23(11):1647-66.

71.Kulig K, Andrews JG, Hay JG. Human strength curves. Exercise and Sport Science Reviews. 1984;12:417-66.

72.Murphy AJ, Wilson GJ, Pryor JF, Newton RU. Isometric assessment of muscular function: The effect of joint angle. Journal of Applied Biomechanics. 1995;11(2):205-15.

73.Izquierdo M, Hakkinen K, Gonzalez-Badillo JJ, Ibanez J, Gorostiaga EM. Effects of long-term training specificity on maximal strength and power of the upper and lower extremities in athletes from different sports. European Journal of Applied Physiology. 2002 Jul;87(3):264-71.

74.Izquierdo M, Ibanez J, Gorostiaga E, Garrues M, Zuniga A, Anton A, et al. Maximal strength and power characteristics in isometric and dynamic actions of the upper and lower extremities in middle-aged and older men. Acta Physiologica Scandinavica. 1999 Sep;167(1):57-68.

75.Baker D. Comparison of upper-body strength and power between professional and college-aged rugby league players. Journal of Strength and Conditioning Research. 2001 Feb;15(1):30-5.

76.Baker D, Nance S, Moore M. The load that maximizes the average mechanical power output during explosive bench press throws in highly trained athletes. Journal of Strength and Conditioning Research. 2001 Feb;15(1):20-4.

77.Newton RU, Murphy AJ, Humphries BJ, Wilson GJ, Kraemer WJ, Hakkinen K. Influence of load and stretch shortening cycle on the kinematics, kinetics and muscle activation that occurs during explosive upper-body movements. European Journal of Applied Physiology and Occupational Physiology. 1997;75(4):333-42.

78.Siegel JA, Gilders RM, Staron RS, Hagerman FC. Human muscle power output during upper- and lower-body exercises. Journal of Strength and Conditioning Research. 2002 May;16(2):173-8.

79.Edgerton VR, Roy RR, Gregor RJ, Rugg SG. Morphological basis of skeletal muscle power output. In: Jones NL, McCartney N, McComas AJ, editors. Human Muscle Power. Champaign, Illinois: Human Kinetics; 1986.

80.Campos GE, Luecke TJ, Wendeln HK, Toma K, Hagerman FC, Murray TF, et al. Muscular adaptations in response to three different resistance-training regimens: specificity of repetition maximum training zones. European Journal of Applied Physiology. 2002 Nov;88(1-2):50-60.

81.Young WB. Transfer of strength and power training to sports performance. International Journal of Sports Physiology and Performance. 2006 June;1(2):74-83.

82.Wisloff U, Castagna C, Helgerud J, Jones R, Hoff J. Strong correlation of maximal squat strength with sprint performance and vertical jump height in elite soccer players. British Journal of Sports Medicine. 2004 Jun;38(3):285-8.

83.Harris NK, Cronin JB, Hopkins WG, Hansen KT. Relationship Between Sprint Times and the Strength/Power Outputs of a Machine Squat Jump. Journal of Strength and Conditioning Research. 2008 Apr 15.

84.Young W, McLean B, Ardagna J. Relationship between strength qualities and sprinting performance. Journal of Sports Medicine and Physical Fitness. 1995 Mar;35(1):13-9.

85.Pearson S, Hume P, Ackland T, Slyfield D. Anthropometry and strength predictors of grinding performance in America's Cup sailors. In: Lamontagne M, Robertson DGE, Sveistrup H, editors. XXII International Symposium on Biomechanics in Sports; 2004 9-12 August; Ottawa, Canada: Faculty of Health Sciences, University of Ottawa; 2004. p. 407-10.

86.Vanderthommen M, Francaux M, Johnson D, Dewan M, Lewyckyj Y, Sturbois X. Measurement of the power output during the acceleration phase of all-out arm cranking exercise. International Journal of Sports Medicine. 1997 Nov;18(8):600-6.

87.Hopkins WG. Sample sizes for magnitude-based inferences about clinical, practical or mechanistic significance (Abstract 2746). Medicine and Science in Sports and Exercise. 2006;38:S528-S9.

88.Hopkins WG. Spreadsheets for analysis of controlled trials with adjustment for a predictor. Sportscience. 2006;10:(sportsci.org/2006/wghcontrial.htm).

89.Cormie P, McBride JM, McCaulley GO. Power-time, force-time, and velocity-time curve analysis of the countermovement jump: impact of training. Journal of Strength and Conditioning Research. 2009 Jan;23(1):177-86.

90.Rimmer E, Sleivert G. Effects of a plyometrics intervention program on sprint performance. Journal of Strength and Conditioning Research. 2000;14(3):295-301.

91.Mayhew JL, Ball TE, Arnold MD, Bowen JC. Relative muscular endurance performance as a predictor of bench press strength in college men and women. Journal of Applied Sport Science Research. 1992;6:200-6.

92.Brown LE, Weir JP. ASEP procedures recommendation I: Accurate assessment of muscular strength and power. Journal of Exercise Physiology online. 2001;4(3):1-21.

93.LeSuer DA, McCormick JH, Mayhew JL, Wasserstein RL, Arnold MD. The accuracy of prediction equations for estimating 1-RM performance in the bench press, squat, and deadlift. Journal of Strength and Conditioning Research. 1997;11(4):211-3.

APPENDIX 1: TEST-RETEST RELIABILITY OF SELECTED GRINDING ERGOMETER MEASURES FOR SAILING PERFORMANCE

Pearson SN, Hume PA, Cronin JB, Slyfield D. Test-retest reliability of selected grinding ergometer measures for sailing performance. In: Schwameder H, Strutzenberger G, Fastenbauer V, Lindinger S, Muller E, editors. XXIV International Symposium on Biomechanics in Sports; 2006 July 14-18; Salzburg, Austria: Department of Sport Science and Kinesiology, University of Salzburg; 2006. p. 546-9.

OVERVIEW

Reliability of grinding performance on a custom-built ergometer was assessed using 18 highly trained America's Cup sailors. Sixteen grinding conditions varied by load (light 39 N m, moderate 48 N m, heavy 68 N m), deck heel (Flat 0° control, Downhill 25°, Uphill 25°, Right 25°, Left 25°), and grinding direction (forward or backward) were examined. Performance measures were peak power (W) and external work over five seconds (kJ). Statistics were difference in mean (M_{diff}), standard error of measurement (SEM) and intra-class correlation coefficients (ICC). External work (SEM = 1.6-6.9%; ICC = 0.91-0.99) was more reliable than peak power (SEM = 1.3-9.6%; ICC = 0.84-0.99). Performance was more consistent when varied by load than by heel condition, and was most reliable in lighter load conditions. Within heel conditions, downhill-uphill tilt was more reliable than right-left tilt. Grinding direction did not appear to affect performance reliability.

INTRODUCTION

Grinding performance in America's Cup racing is an important determinant of overall boat speed. Grinding winches are responsible for the movement of the sails and therefore provide the power behind tacking and gybing (where the yacht crosses the wind to change direction). In addition the winches are used for trimming the sails which changes the angle the yacht is headed and the efficiency of wind usage.

To monitor the effects of various technique changes, training schemes or other performance enhancing interventions on grinding performance an instrumented grinding ergometer was built. When assessing the reliability of a testing procedure it is important that the assessment be as specific as possible to race conditions as there may be a number of factors that may alter the level and consistency of performance. With this in mind the ergometer (Dynapack, Wellington, New Zealand) was constructed using standard on-board grinding hardware to ensure familiarity for the sailors. Grinding performance can be influenced by a number of conditions such as grinding direction (forward or backward depending on what gear the winches are in), system resistance, and deck heel (tilt). System resistance (load on the grinding winches) increases with wind strength and sail position relative to wind direction, while heel is the sideways lean of the yachts' deck when sailing up-wind, which can increase with wind strength up to 25-30°. Deck heel was included in this study, as an area of research interest is the influence of deck-layout on grinding performance, in particular, what differences in performance there may be between grinding pedestals orientated fore-aft (resulting in left-right/medio-lateral tilt when grinding under heel conditions), and pedestals orientated across the boat (uphill-downhill/anterior-posterior tilt).

Quantifying trial to trial performance variation in grinding for each of these conditions is essential for monitoring performance. For a test to be valuable it must be specific enough to measure the variable of interest but also reliable enough to detect the relatively small differences in performances that are beneficial to elite athletes [10]. A reliable test is one with small changes in the mean, a low standard error of measurement (SEM), and a high test-retest correlation between repeated trials [6]. The purpose of this study was therefore to quantify the variability in grinding performance under different load, direction, and heel conditions.

METHODS

Data Collection: Ergometer testing was divided into two rounds on separate days (Load, Heel) for the effects on reliability of peak power (W) and external work over five seconds (kJ) for both forward and backward grinding. Male America's Cup sailors who performed grinding routinely participated in this study; 18 completed load testing and 9/18 completed heel testing (due to availability). The grinding ergometer was set up with standard pedestal (870 mm vertical) and crank arm (250 mm) dimensions for a main sheet grinding pedestal on an America's Cup class yacht. Gearing for the ergometer was linked through a multiple-speed dynamometer set up to output a number of grinding performance measures. Ergometer hydraulic load was applied using a dynamic closed loop controller. For each round, the sailors completed a self-selected warm-up on the grinding ergometer, then a maximal trial of all conditions once within a single session, with the session repeated 5 hours later. All grinding trials were maximal effort, eight-seconds in length, and separated by a 3-5 minute rest period, with verbal "go" and "stop" signals the only in-trial feedback.

Round 1 - Load testing: Both forward and backward grinding were tested using three torque loading conditions; 39 N m (Light), 48 N m (Moderate), and 68 N m (Heavy). All 18 sailors completed the light and moderate loads but due to the physical requirements for grinding effectively at the heavy load only the six sailors regarded as primary grinders completed the heavy load condition. Load conditions were randomised, with trials alternating between forward and backward grinding to reduce the possible influence of fatigue by alternating the prime-mover muscle groups. The session was completed in 40 minutes.

Round 2 - Heel testing: Forward and backward grinding performance of nine sailors was tested for five heel conditions: Flat (0°), downhill (grinding from above the pedestal with 25° deck heel), uphill (from below at 25°), right (with right side of the body on the high-side of the pedestal at 25°), left (left side high at 25°). All conditions were against the same moderate 48 N m load. The 25° angle was selected as an upper range heel angle experienced in racing conditions, and angles were verified for the ergometer platform using a SmartTool™ digital spirit level (M-D Building Products, Oklahoma, USA). Heel condition order was randomised, with trials alternating between forward and backward. The session was completed in 60 minutes.

Data Analysis: Descriptive statistics for all variables are represented as mean and standard deviations. Data for external work (kJ) and peak power (W) were log transformed to provide measures of reliability as standard error of measurement (SEM). Intra-class correlation coefficients (ICC) were calculated. Presence of significant systematic discrepancy between reliability measures of different conditions was determined using a two-tailed unpaired *t*-test.

RESULTS

There were small changes in the group means for peak power and external work performed under all directional and loading conditions (see Table 1). Average SEM across all conditions was similar for external work and peak power (3.1 and 3.3% respectively) but less variation was observed for external work (1.6-3.9%) than peak power (1.3-5.4%). SEM tended to increase with load for both forward and backward grinding.

Between-test differences in mean peak power and mean external work were larger for heel direction testing (0 to 4.3%) than for load testing (0.1 to 2.1%). SEM was lower for external work than peak power in seven of the ten conditions, and on average (external work = 5.5%, peak power = 6.1%). External work SEM (4.6-6.9%) was less variable than peak power SEM (3.5-9.6%). SEM was significantly greater in right-left heel conditions than uphill-downhill heel conditions for both peak power (p = 0.028) and external work (p = 0.030) (Table 3). Test-retest intra-class correlation coefficients were all 0.92 or greater.

Table 1. Reliability of grinding performance during different load conditions.

	Test 1	*Test 2*			
Grinding condition	Mean ± SD	Mean ± SD	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

Note: n=18 sailors except n=6 for heavy load conditions.

Table 2. Reliability of grinding performance during different heel conditions at a load of 48 N m (n=9 sailors).

Grinding condition	*Test 1* Mean ± SD	*Test 2* Mean ± SD	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

DISCUSSION

Variation in grinding performance was small across all load conditions, with the least variation observed with light load backward grinding and the most variation with heavy load forward grinding. Performance became increasingly more variable in both forward and backward grinding as load increased. A similar pattern was seen in the ICC's with the relative consistency of performance between individuals decreasing as load increased. An additional factor which affected the apparent variability at heavier load grinding was the fewer subjects completing the trials at the heavy load compared to the moderate and light loads. As heavy load trials only included the most accomplished grinders the standard deviation for the heavy load conditions was lower than for the moderate load conditions, however, the low statistical power associated with low subject numbers led to a higher SEM. Nevertheless, based on current results a change in external work of over 4% or a change in peak power of over 5.5% can be interpreted with a fair degree of certainty under any loading condition.

Testing at different heel angles was considerably more variable than at different loads on a flat (0°) heel. Although the difference in the mean was never more than 5% for any heel condition, SEM varied from 3.5% (forward grinding from below at 25°) to 9.6% (backward grinding, right-hand side high at 25°) for peak power and between 4.6% (backward grinding at 0°) and 6.9% (forward grinding, right-hand side high at 25°) for external work. Performance changes can therefore only be interpreted with any confidence if they are over 7% for external work or 10% for peak power. While in some circumstances a standard error of measurement under 10% may be considered small [11], it is important to interpret levels of error in their relevant context, and in the case of America's Cup grinding performance a level of closer to 5% is more appropriate. Higher variability in the heel testing compared to the load testing is likely to be a result of a reduction in base of support stability when shifting from a flat to a tilted surface. However, reliability could be improved with development of the testing protocol. The heel testing sessions involved 10 maximal grinds at a moderately heavy load making it a more intensive session due to the volume of work performed. By altering the number of grinds performed and/or recovery time the influence of fatigue and performance variability may be reduced. This contention is supported by the greater variability in both the forward and backward flat conditions within the heel testing when compared to a similar condition in the load testing (forward and back, moderate load) where grinders performed only four to six grinds. The influence of either physiological or mental fatigue from the longer session may have affected reliability.

While there is little difference in reliability between external work (kJ) and peak power (W) when grinding load and direction are varied, peak power is substantially less reliable when deck heel is involved. While there was little difference between the ICC values overall, only five of the total 16 conditions tested had a lower level of absolute variability (SEM) in peak power than external work. While a high correlation indicates good repeatability in terms of relative rankings, the ability to accurately quantify absolute changes in performance is generally more important when examining the effect of any kind of intervention.

CONCLUSIONS

External work appears more reliable than peak power as a means of quantifying grinding performance, although peak power may still be useful in flat heel conditions. Using current protocols the SEM for external work was up to 4% in different load conditions and up to 7% for heel conditions. A change of 5-10% in grinding performance would be considered substantial and therefore it would be beneficial to improve the precision of measurement, especially in terms of heel condition testing, in order to be confident of detecting changes of a smaller magnitude. External work is more appropriate for assessment of grinding performance than peak power as it is important to the performance of the boat for power output to be maintained over a period of time.

APPENDIX 2: GRINDING SIMULATOR TILT STUDY REPORT

Pearson SN, Hume PA, Cronin JB, Slyfield D. Grinding simulator tilt study report. Auckland, NZ: Institute of Sport and Recreation Research New Zealand, Auckland University of Technology; 2005 March 2005. 6 pages.

Grinding simulator tilt study report

A technical report for Emirates Team New Zealand

March 2005

Prepared by:
Simon Pearson, Associate Professor Patria Hume, Associate Professor John Cronin
Institute of Sport and Recreation Research New Zealand,
Division of Sport and Recreation, Auckland University of Technology

Reviewed by David Slyfield
Emirates Team New Zealand

AUT
AUCKLAND UNIVERSITY OF TECHNOLOGY
TE WĀNANGA ARONUI O TAMAKI MAKAU RAU

Emirates TEAM NEW ZEALAND

AIM

To test the effect of tilt on grinding performance on the grinding ergometer (simulator).

METHODS

Single person trials protocol

Sailors were tested in two one-hour test sessions on the same day, with more than one hours rest between the two blocks of tests.

Each block of tests consisted of 10 grinds (i.e. 20 grinds over-all). In each block two grinds were done on a flat surface and 8 grinds on a 25 degree sloped surface. Four of the sloped grinds were on a slope as if grinding upwind in our current primary pedestal configuration (here after referred to as “conventional”). The other four sloped grinds were on a slope as per the One World primaries and our current mainsheet and traveler pedestals (here after referred to as “in-line”). Test conditions (not in the order tested):

1. Flat forward*
2. Flat backward
3. Conventional forward – left hand upwind
4. Conventional forward – right hand upwind
5. Conventional backward – left hand upwind
6. Conventional backward – right hand upwind
7. Inline forward – standing above the pedestal
8. Inline backward – standing above the pedestal
9. Inline forward – standing below the pedestal
10. Inline backward – standing below the pedestal

**Forward grinding means that the handles are rotating away from the grinder at the top of the rotation.*

The order of the trials was reverse randomized, so that across the two blocks of trails fatigue should not be a contributing factor.

The 25 degree slope was chosen because it should be steep enough to show differences between the different configurations. At maximum heel on the boat (i.e. >30 deg) grinding is usually only performed for small trim ups – a lot of the work performed in grinding occurs though the roll of the tack.

Two groups of sailors were tested. The first was made up of 3 grinders and a mastman. The second consisted of 4 bowmen and a mastman. The grinding resistance for the second group was lighter than for the first group (high 100 resistance). For both groups the resistance would be described as hard. The resistance was selected so that for each group the handle speed would be around 100 rpm. Handle speed in fact varied across all floor orientations from 140 – 65rpm across different individuals in the grinder group. For the bowmen group rpms varied from 160-90.

Grinds were for 8 seconds, proceeded by a rolling 3 second start. From the 8 seconds of data, the best 5 seconds of data was taken for analysis, as in some trials some individuals have a delay in reaching peak power.

Foot placement and body position were self selected by the sailors.

Two person trials protocol

The test protocol was exactly as per single person trials but with one person on each side of the handles.

Sailors were paired so as to represent various arrangements that could occur on the boat. These were:

2 x big-guy, little-guy, (grinder-bowman) pairings

1 x big-guy, big-guy (grinder-grinder) pairing

3 x smaller guys of relatively even strength pairings

Since the single person trials the controller system on the dyno was replaced due to malfunction in the power supply. Therefore comparing absolute resistance numbers dialed into the machine between the single and two person trails needs to be treated with caution.

The load selected for two person grinding was effectively the hardest that could be handled by the dyno (without major belt slippage) with two people on the handles. RPM data for the two person testing showed that majority of trials occurred with handle speeds between 95 & 137rpm. There were some trails faster and slower than this. Therefore the two person data seems close to the single man grinder trials.

The only other change to the grinding simulator set up for the two person trails was that the non-skid was significantly improved and a set of chocks was placed across the centerline of the cockpit.

Simulator malfunctions

In the first 1 hour block of two person grinding two problems with the simulator occurred. The drive belt jumped a number of times in trial 5 (conventional forward) and trial 8 (conventional backward). The drive belt also moved sideways (as it appeared to be slightly misaligned) probably creating more friction. Therefore two of the four conventional trails in round one of two person testing were adversely affected. Modifications to the machine were made before round two of testing and no mechanical problems occurred in round two.

RESULTS

Single person trials results

On average both the In-line and Conventional systems have 5% lower power output at 25 degrees compared to flat grinding.

Averaged across all grinding conditions the In-line system showed 0.4% greater power output than the Conventional system – i.e. no significant difference. In a nutshell this occurred because the sailors tested were stronger (compared to conventional) when grinding forwards from below, but weaker when grinding backwards from above. The net effect is no significant difference between the two systems.

For combined group data the order of performance in sloped conditions were:

1. Forwards standing below
2= Forwards standing above (6% worse than standing below)
2= Forwards conventional (6% worse than standing below)

4. Backwards standing below
5. Backwards conventional (2 % worse than backwards standing below)
6. Backwards standing above (14% worse than backward standing below)***

****** please read two person trail information ("why the differences") which explains that this 14% reduction in power is probably a function of floor grip.*

All backward grinding conditions were weaker than forward grinding conditions, which is consistent with what we have previously found. The average loss in power when grinding backwards (averaged across all slopes) is 15%. The strongest forward position (forwards standing below) may be as much as 25% better than the weakest backward condition (backwards standing above).

Richard Karn reported that in the One World testing In-line was favored under all load conditions and handle speeds. There was also a clear trend in the One World testing that the heavier the load got the more the in-line system was favored. It appears that the Team New Zealand testing may have shown a similar trend. All sailors in the "grinder" group (harder relative resistance/slower handle speed) showed a small favoring (1 to 2.6%) for the In-Line system. All sailors in the "bow" group showed a small favoring (0.7 to 2.8%) for the Conventional system. Therefore the ETNZ data may indicate a "cross over" in the performance of the two systems not seen in the One World testing.

Two person trials results

The combined group data shows that for round 1 of two person testing the advantage for the inline system was 10.6% and in round two the advantage for the inline system was 7%.

If you replace the conventional trials in round 1 affected by simulator malfunctions with the data from round two then the favoring for the inline system in round 1 becomes 9.1%.

These differences are in the order of what One World apparently saw in their testing.

From the single person data we could theorize that the best arrangement of sailors of dissimilar size in the inline system would be to have a big guy below grinding forwards from below and a small guy grinding backwards from above. The worst arrangement should be reversing this arrangement. It however appears from the pairings that were tested, that no matter which way the two guys are arranged in an inline system, they still perform better than any conventional pairing.

What appears most important in an in inline system is to have the big guy grinding forward if possible, and if they are grinding backwards in a pair, it is better is they are below than above.

DISCUSSION

Why the difference in results between the one person and two person trials?

Firstly I believe that advantage shown for the inline system in the two person trials was a “real” advantage, not one created through differences in the dynos performance at different tilts.

In tilting the machine the belts and drive chain all move as one unit and so no significant changes in stretching etc should occur. The *specific* request to the constructors of the machine (International Dynomometers) was to build a machine that would show the differences in grinding performance at various tilts. As precision engineers I trust their ability to build a machine that performs evenly on all tilts (hydraulically and mechanically). I have checked with them since the two person testing and they state that any difference in hydraulic pressure on opposing tilts would be negligible as it is a closed hydraulic system.

After correcting for the belt misalignment seen in round one of two person testing the belts stayed perfectly in alignment for all of round two. Therefore the validity of round one test results *could* be disputed but not round two. Recall also that if you replace the conventional trials in round 1 affected by simulator malfunctions with the data from round two then the favoring for the inline system in round 1 is still 9.1%.

A number of sailors said that they thought the resistance of the machine was harder in the conventional tilt during two person testing and thought it was the machine performing differently. The alternative would be that it was themselves performing differently.

I took part in the two person testing myself to see how it felt personally. I cannot say that I noticed a change in the performance of the machine between conventional and inline tilts.

I can think of two reasons why the inline system may have performed better in the two person trials. Firstly the use of far better non skidding and addition of chocks allowing stronger foot placements. In looking at the single person and two person grinding data in conjunction I now believe that the extremely poor performance in backward grinding from above in the single person trials was partly a function of the lack of floor grip.

Secondly in solo grinding there are noticeable “dead-spots” (low power sections) in the 360 degree cycle. With two people these are smoothed out. The relative amount of “dead-spot smoothing” may be greater for solo vs two person grinding when in an inline set up.

CONCLUSION

Through the length of a race a sailor will find themselves:

A. Either above or below the handles (in an inline system)

B. Sometimes grinding alone or in pairs

C. Sometimes going forwards and sometimes going backwards.

The overall ratio of biomechanical advantage in the in-line system as indicated by our test results is between 5-10%. Arranging people in their most effective positions in relation to the floor slope and grinding direction may decrease or increase this advantage.

Regardless of what happens with the primary pedestal arrangement the information gained through this testing should be used to improve our arrangement of sailors on the mainsheet and runner pedestals during manoeuvres.

APPENDIX 3: THE INFLUENCE OF TECHNIQUE ON GRINDING PERFORMANCE

Pearson SN, Hume PA, Cronin JB, Slyfield D. The influence of technique on grinding performance. A technical report for Emirates Team New Zealand. Auckland: Institute of Sport and Recreation Research New Zealand, Auckland University of Technology; 2006 June. 20 pages.

The influence of technique on grinding performance

A technical report for Emirates Team New Zealand

June 2006

Prepared by:
Simon Pearson, Associate Professor Patria Hume, Associate Professor John Cronin
Institute of Sport and Recreation Research New Zealand,
Division of Sport and Recreation, Auckland University of Technology

AUT
AUCKLAND UNIVERSITY OF TECHNOLOGY
TE WĀNANGA ARONUI O TAMAKI MAKAU RAU

Reviewed by David Slyfield
Emirates Team New Zealand

Emirates TEAM NEW ZEALAND

KEY POINTS

Aim of the report

To outline what might be good and poor technique for grinding, based on strength, video and SRM data collected over the last year.

Method of data collection

Ten sailors completed forward and backward heavy and light grinding, with the grinding pedestal instrumented with SRM cranks, and the sailors instrumented with video markers and muscle activity markers.

Practical implications of the report

Maximal torque application for backward grinding occurs through ~300-40°, and occurs at ~60-200° for forward grinding. These patterns have implications in terms of conditioning for grinding, with the possibility of making the movements trained in the gym more specific to the key motions in grinding. For example, the specificity of joint angles during certain exercises can be improved. In almost all cases those who performed worse in grinding than their strength had predicted had a lot of anterior-posterior (forward-backward) movement of the head and trunk. In contrast, those who performed equal to or above their strength kept the midline fairly stationary while rotation occurred around it.

Forward grinding: Force should be applied as evenly as possible throughout the whole cycle. While there are certain phases in which more force can be applied, concentrate on trying to maintain the pressure on the handles and grinding in circles as much as possible. Balance and trunk stability should be maintained as much as possible. Rotation at the hips and shoulders is an essential part of grinding, but the midline of the trunk should remain fairly stationary, resulting in less energy wastage and better maintenance of balance.

Backward grinding: Pulling strongly and generating power across the top of the crank arm rotation is the key phase of backward grinding in terms of performance. Pushing through the underside of the rotation is also beneficial in terms of maintaining momentum of the handles, but not as crucial as the pull across the top. As with forward grinding, maintaining trunk position provides a better platform from which to base the grinding movement. Keeping a balanced position will allow repeated powerful pull phases across the top, rather than a good one and then a period of imbalance and adjustment. Keeping knees bent and getting lower will result in a stronger position for the key pull phase across the top of the crank arm rotation. However, stability should not be sacrificed when doing this so it is important to keep foot position and distance from the pedestal balanced.

Next steps

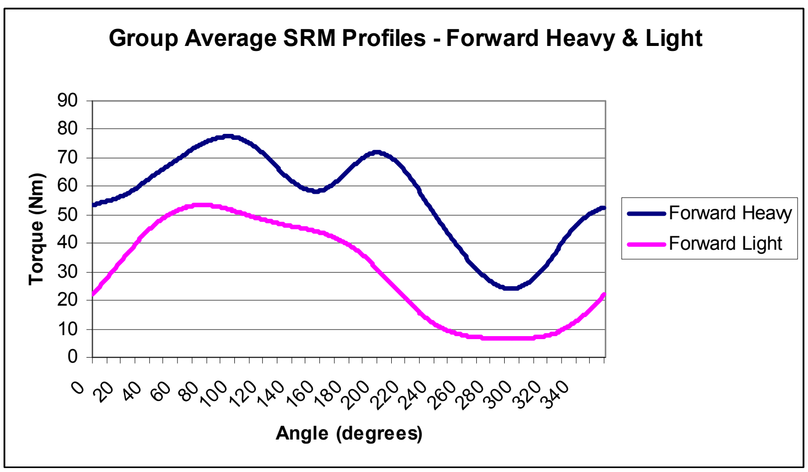
The SRM profiles will be combined with EMG (muscle activation) and kinematic (body position/movement) data to enable us to make more definitive recommendations on the conditioning for grinding.

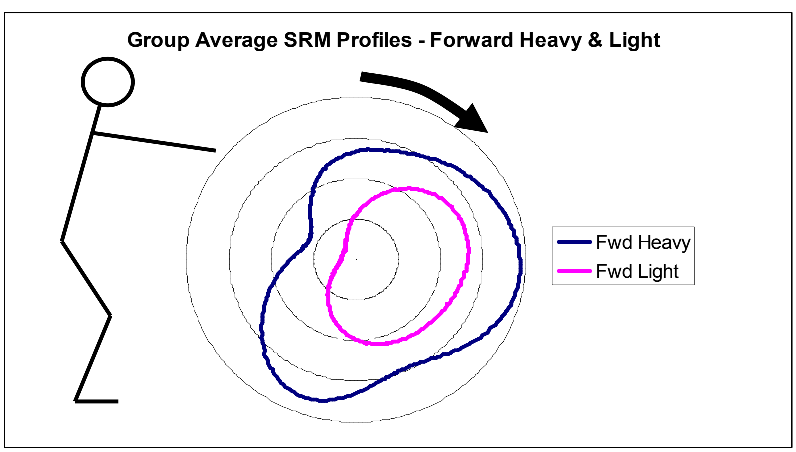
INTRODUCTION

From testing previously conducted we have established that strength is the single most important factor in grinding performance, especially in higher load conditions. Maximal strength (1RM) determines 70-90% of grinding performance (depending on direction, load condition, etc), with the remaining 10-30% being explained be other factors such as technique. Technique incorporates a variety of factors and this report outlines what might be good and poor technique, based on video and SRM data collected over the last year.

SRM PROFILES IN DIFFERENT GRINDING CONDITIONS

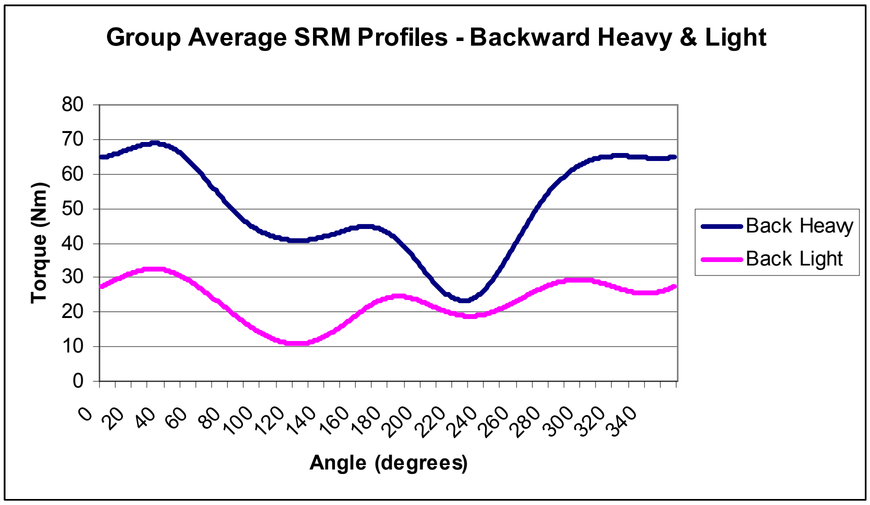
An SRM is a strain-gauged device that measures the torque (essentially force) applied to the grinding handles throughout a cycle. The SRM collects position and torque readings at 500Hz, enabling us to get a high-definition "picture" of how force is applied throughout a cycle. Although individuals vary in how they apply torque through a grinding cycle, there were certain patterns that presented themselves for the different grinding conditions tested. We tested both forward and backward grinding at a light and moderate/heavy load. It is important to note that for the testing involving the SRM's these loads were not absolute; rather, they were relative loads customised to the individual sailor so that everyone was grinding in approximately the same rpm range for the different load categories (i.e. 190-160 rpm for light, 120-90 rpm for heavy).

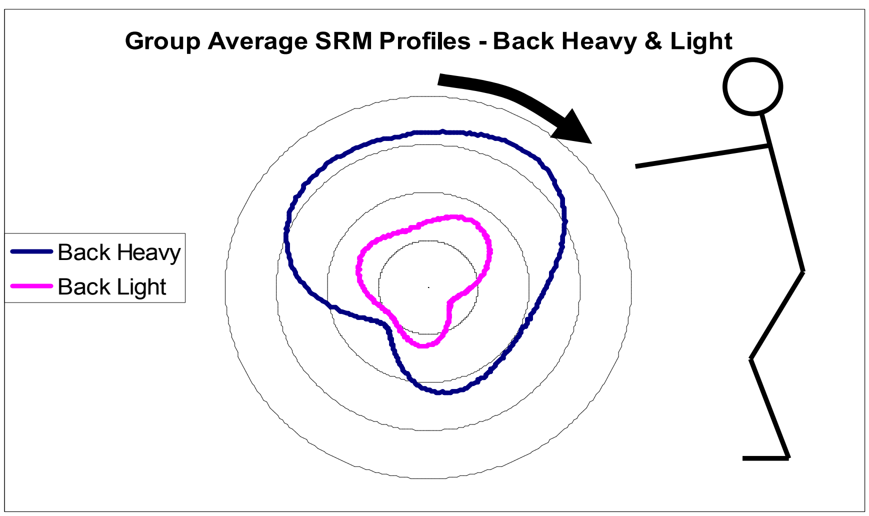




Figures 1A & 1B: Average torque-angle profiles for forward grinding conditions (10 sailors), represented in two graphical forms.

For each sailor we averaged the SRM profiles for six consecutive cycles near the beginning of the trial to determine their force application profile. These individual profiles were then combined to provide a "typical" profile for each of the grinding conditions, seen in Figures 1 & 2. For all conditions 0° represents the grinding crank handle pointing vertically upwards, with the trace then continuing positively in the direction of movement (away from the body for forward, toward the body for backward). It should be noted that due to only having one SRM system the traces are for one side only – right hand for forward and left hand for backward.





Figures 2A & 2B: Average torque-angle profiles for backward grinding conditions (10 sailors), represented in two graphical forms.

The noticeable characteristics of these profiles are the location of the maximal torque and the variability of torque application throughout the cycle. While maximal torque application for backward grinding occurs through ~300-40°, it occurs at ~60-200° for forward grinding. In addition, the application of torque is more variable throughout the cycle when grinding in heavier load conditions. Both observations are consistent with our previous assumptions of how force is applied during grinding, namely:

- There is a main force/torque application phase that "drives" the rotation. This phase occurs on the down-stroke (pushing away) of forward grinding, and in the "pull" across the top of the cycle in backward grinding.
- These phases are exaggerated, with more variation in torque application, when there is more load on the system.

This confirmation may have implications in terms of conditioning for grinding, with the possibility of making the movements trained in the gym more specific to the key motions in grinding. However, we will be able to make more definitive statements on this aspect once the SRM profiles have been combined with EMG (muscle activation) and kinematic (body position/movement) data.

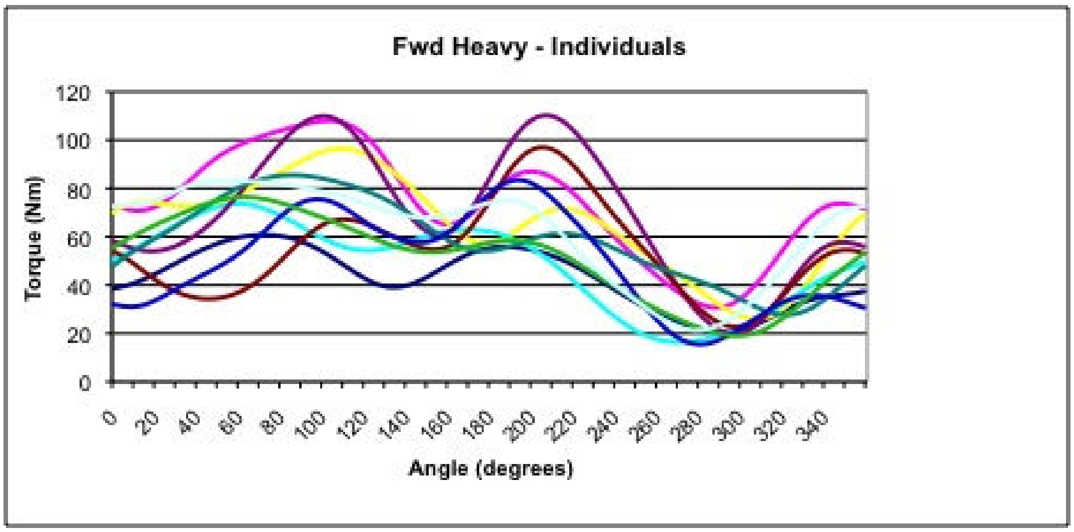


Figure 3: Individual torque-angle profiles for heavy forward grinding.

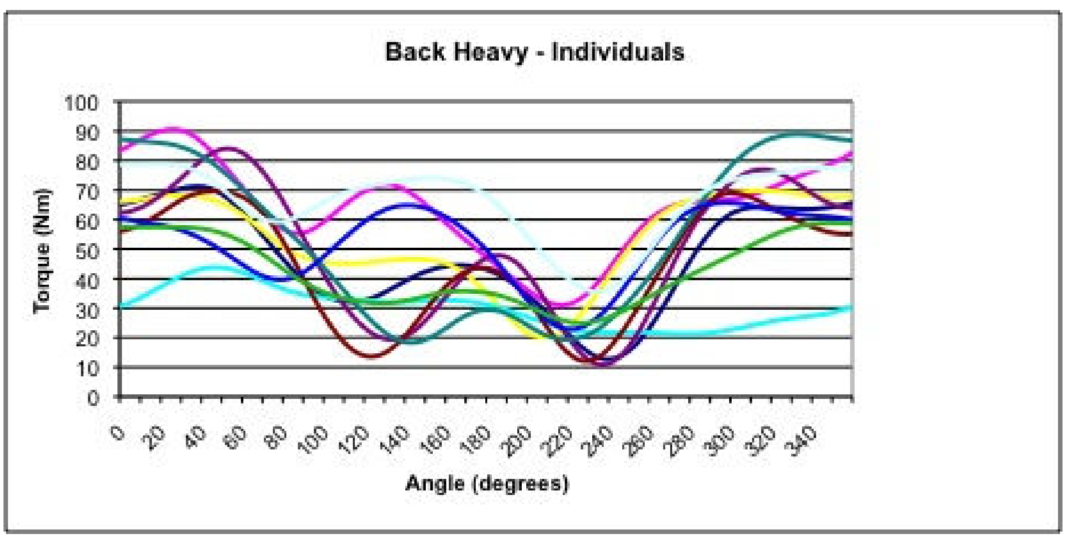


Figure 4: Individual torque-angle profiles for heavy backward grinding.

From the individual SRM profiles presented in Figures 3 and 4 we can see that although there is a common pattern to most of the profiles, there is considerable variation between individuals. One factor which contributes to this variation is the difference in body position which can be observed between individuals (see photos at the end of this report), and can have a substantial influence on the direction of force application. By correcting angles on the SRM profile for body position we can get an indication of how individuals grind relative to their body position. One example of this is measuring the angle at which the sailor is pushing or pulling (depending on grinding direction) at the point where maximum torque occurs (see Table 1). As we have already established that there is a principle drive phase for both forward and backward grinding, this type of measurement can provide information that may be used in physical conditioning, for example to improve the specificity of joint angles during certain exercises.

Table 1. The angle of force application at peak torque of the main drive phase (push for forward, pull for backward).

	Forward (°)	***Backward (°)***
Sailor 1	90	80
Sailor 2	75	80
Sailor 3	70	80
Sailor 4	100	70
Sailor 5	90	80
Sailor 6	75	80
Sailor 7	70	90
Sailor 8	90	85
Sailor 9	85	95
Sailor 10	90	90
Mean±SD	***83.5±10.3***	***83.0±7.1***

Note: Angles are measured relative to an individual's trunk. Measurements are rounded to 5° for the sake of simplicity and due to limited precision of measurement. An optimal angle for a sailor needs to take into consideration the muscle lever arm attachment lengths.

RELATIONSHIP BETWEEN SRM PROFILES AND GRINDING PERFORMANCE

As mentioned previously, strength is the main predictor of grinding performance, but we want to get a better idea of what makes up the remaining 10-30% of grinding performance. The SRM's give us one way to objectively assess the grinding performance.

Because what we are looking at in this situation is essentially a "shape" output from the SRM, rather than a single value performance measure like power output, objectively determining the influence of the torque profile is not a straightforward procedure. One area which we believed would influence performance was the consistency of torque application throughout the cycle. Using various statistical procedures we were able to get a handle on what was beneficial from a technique point of view (See Table 2), by:

- Correcting grinding performance scores for strength - working out a predicted performance score based on strength and seeing how much the actual performance deviated (either positively or negatively) from the predicted. The strength score used was the "actual" 1RM (rather than a predicted score) from the Smith machine testing performed in February-March 2006.
- Calculating a variability score for torque application over 360°.
- Plotting the strength-corrected grinding performance score against the variability score from the SRM profile to see a relationship.

Table 2. Relationship between grinding performance and variability of torque application through 360°.

Grinding Condition	*Subjects (n=)*	*Correlation*	*Certainty*
Fwd – Med Load	9	-0.60	92%
Fwd – Heavy Load	6	-0.25	61%
Back – Med Load	9	0.48	85%
Back – Heavy Load	6	0.61	86%

The information in Table 2 indicates that the importance of variation in torque application differs between forward and backward grinding. It is important to note that this is a general picture and as individuals differ in their mechanical set-up (levers, fibre-types etc) there is no "perfect" technique that fits everyone, but there are some general patterns that we can learn from.

In forward grinding, there is a negative relationship between torque variation and performance. This means the more consistently force is applied around the cycle, the better the performance, although this appears to be less important in heavy load grinding. A reason for this may be the inability of the musculature to generate the higher forces required at heavy loads through certain motions of the cycle, e.g. the "lifting" phase (close to the body) at the end of the forward grinding cycle. This is not to say that trying to maintain torque application during this phase is not important, but that, due to physical limitations, a higher proportion of the work performed to create the movement is now being performed through the stronger planes of motion.

In contrast to forward grinding, backward grinding performance has a positive relationship with variation in torque application. This suggests that the individuals who grind better than their strength would predict have a more uneven pattern of torque application throughout the cycle. A closer look at the SRM profiles shows that this is primarily due to a greater relative input during the strongest phases of the movement – primarily the "pull" across the top of the cycle, and secondly a "push" through the bottom of the cycle.

Tables 3 and 4 show historical grinding performance relative to strength testing, for the sailors who completed SRM testing. A negative score indicates that an individual performed worse in their grinding test than their strength would predict, while a positive score indicates they performed better. Sailors are divided into those who grind above, below, and equal to what their strength would predict. This data allows us to get an idea of who is generally a "good", "average", or "poor" grinder from a technique point of view.

Table 3. Forward grinding performance relative to strength for the heaviest load completed in each session, with an overall rating for each sailor.

	Feb06	Feb06*	Apr05	Feb02	Dec01	Sep01	**Mean**	**Grinding relative to strength**
Sailor 8 (+)	2	0	21				**8%**	**above**
Sailor 4 (--)	-11	-11	-15				**-12%**	**below**
Sailor 1 (++)	10	8	14				**11%**	**above**
Sailor 6 (-)	-3	-3		-3		-1	**-2%**	**equal**
Sailor 5 (--)	-8	0	1	-6	-10	-8	**-5%**	**below**
Sailor 10 (+)	11	2	6	6	2	5	**5%**	**above**
Sailor 7 (+)	7	0	2	0	5	5	**3%**	**equal**
Sailor 3 (-)	-3	7	-3	-6	-8	-2	**-2%**	**equal**
Sailor 2 (=)	-3	-2	-2	9	12		**3%**	**equal**
Sailor 9 (=)	-1	-4	-3				**-3%**	**equal**

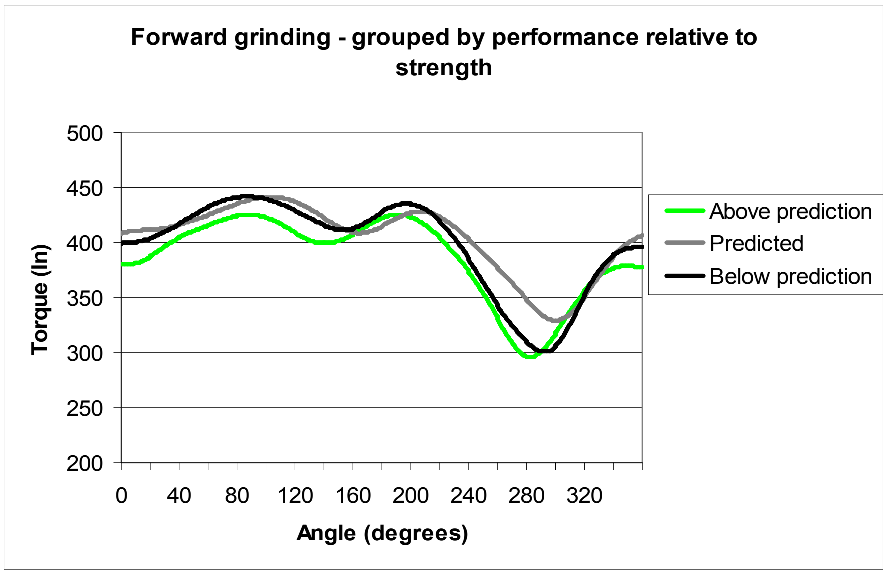
*Calculated using the 1RM strength score determined in Smith machine testing.

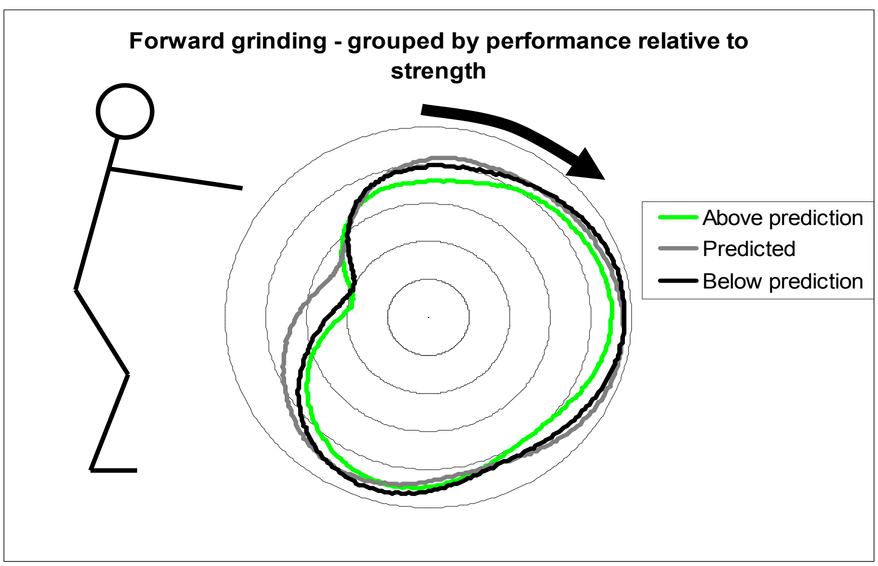
Table 4. Backward grinding performance relative to strength for the heaviest load completed in each session, with an overall rating for each sailor.

	Feb06	Feb06*	Apr05	Feb02	Dec01	Sep01	**Mean**	**Grinding relative to strength**
Sailor 8 (-)	-5	-3	0				**-3%**	**equal**
Sailor 4 (--)	-11	-9	-20				**-13%**	**below**
Sailor 1 (++)	9	7	19				**12%**	**above**
Sailor 6 (=)	-3	6		-8		0	**-1%**	**equal**
Sailor 5 (++)	2	0	11	11	9	-2	**5%**	**below**
Sailor 10 (=)	-3	-8	-4	1	-1	2	**-2%**	**equal**
Sailor 7 (=)	6	2	2	-9	-3	0	**0%**	**equal**
Sailor 3 (--)	-24	-8	-14	4	-7	0	**-8%**	**below**
Sailor 2 (++)	12	9	6	2	2		**6%**	**above**
Sailor 9 (+)	10	0	-2				**2%**	**equal**

*Calculated using the 1RM strength score determined in Smith machine testing.

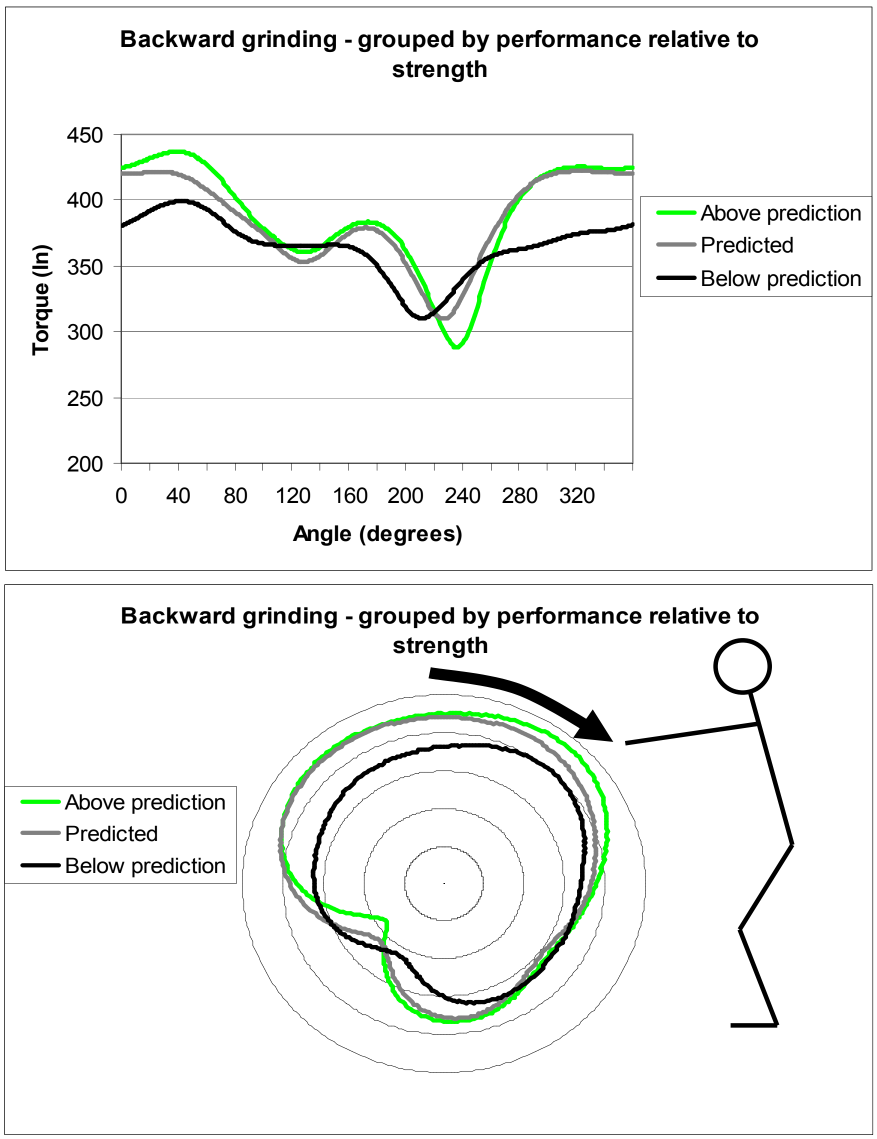
Strength has always predicted forward grinding better than it predicts backwards grinding, suggesting that forward grinding technique does not vary greatly between individuals. Looking at the grouped data (Figures 5A & 5B), that would seem to be the case, however, when looking at individual traces it is apparent that the way in which force is applied throughout the cycle does vary substantially between individuals, although not necessarily in a uniform manner that would show up in an averaged trace. The only consistent pattern to show up is that the "better" grinders tend to apply force more consistently throughout the cycle, as discussed previously.





Figures 5A & 5B: Forward grinding profiles grouped by performance relative to strength.

Figures 6A & 6B show the SRM profiles for heavy load backward grinding with the group again divided into those who grind above, below, and equal to what their strength would predict. There is little difference in the shape of the profile between those who grind above and equal to their strength – they are bi-phasic, with torque application peaking noticeably through the top ~100° of the cycle and a smaller push phase across the bottom. In contrast, the group who grinds below their strength is considerably flatter, most noticeably through the strong pull movement across the top of the cycle. This pattern is also evident on an individual basis, showing that it is not a pattern created artificially by averaging. Although it seems intuitive that maintaining torque application throughout the cycle should be beneficial to grinding performance, the results here indicate that consistency should not be sustained at the expense of power through the strongest movement phases.



Figures 6A & 6B: Backward grinding profiles grouped by performance relative to strength.

KINEMATICS/BODY MOTION AND PERFORMANCE

The movement and position of the body has a major influence on the magnitude and direction of forces applied to the handles, and therefore grinding performance. For example, in our study in the 2003 campaign we showed how a relatively simple shift in body position (lowering the trunk position) could improve heavy load backward grinding performance by an average of 5% across the group.

In this next section of the report we have categorised the sailors into good, average, or poor grinders according to their performance relative to maximal strength, and looked at patterns in force/torque application at the handles. As a follow on from this a qualitative assessment of grinding technique has been performed from video footage to try and identify other aspects which may characterise good or poor grinding technique. The one characteristic that, in almost all cases, differentiated those who were grinding below their strength from those who were grinding equal to or above their strength, was overall stability. Due to the nature of the grinding movement there is always rotation of the trunk in the transverse plane – if you are looking from directly above the grinders head, you would see one shoulder/hip moving forward and the other moving back around a central pivot point or midline (see Figure 7). However, in almost all cases those who performed worse than their strength also had a lot of anterior-posterior (forward-backward) movement of the head and trunk. In contrast, those who performed equal to or above their strength still had transverse plane rotation of the trunk but very little other trunk movement, with the midline staying fairly stationary while rotation occurred around it. This could be seen in both forward and backward grinding (heavy load), with only two out of the ten sailors examined not fitting the pattern for each direction.

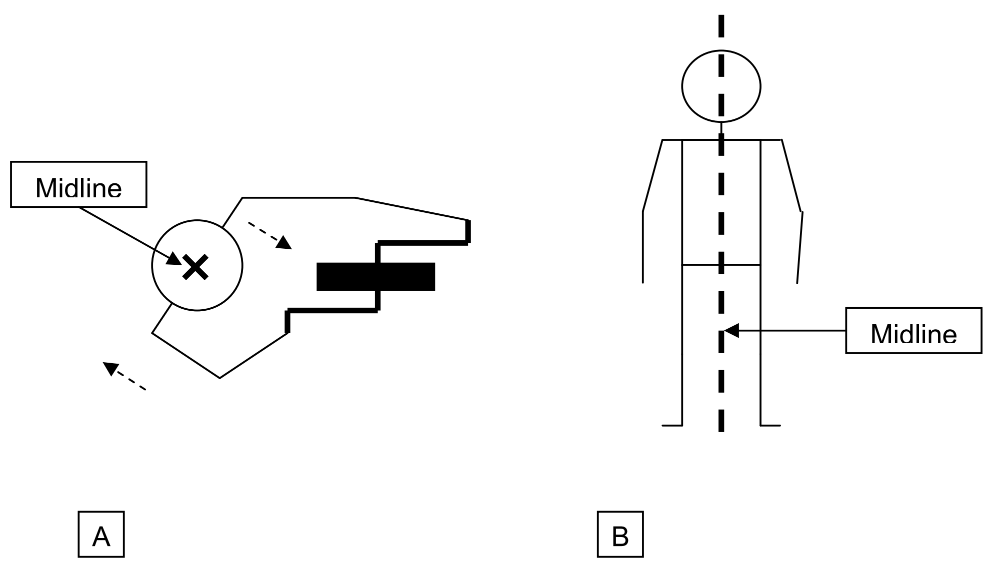


Figure 7: Transverse plane shoulder rotation during grinding as seen from above (A) and the theoretical midline/pivot point for rotation (B).

Having a stable platform from which to work from is beneficial to almost all sporting movements as it allows greater movement control; applying the right forces at the right time in the right direction. Anterior-posterior movement of the trunk and head during grinding will result in a shift in the body's centre of mass and therefore the point of balance. Having to constantly adjust for this shift in balance is not only inefficient in terms of muscle usage, but is also likely to negatively influence ability to apply useful force to the handles. Using forward grinding as an example, "throwing" yourself into the push phase across the top of the rotation may increase the force applied through that section but is likely to compromise force application through the following underneath (pull) part of the rotation, and the push across the top with the opposite hand, due to continually having to adjust balance.

While the difference in trunk stability was a constant pattern throughout almost all of the sailors involved, it is difficult to make any other conclusive statements due the variation in techniques employed by the individual sailors. However, Table 5 outlines some of the main points which characterise each individual's technique. Still images taken from video of each of the ten sailors during heavy load grinding trials, both forward and backward and at two points during the cycle, are also included in Appendix 1.

Table 5. Grinding characteristics for individual sailors.

Sailor	***Technique comments (including rating)***
Sailor 1	*Forward (++):* Stands reasonably far back from pedestal, pushing more across than down for the main push phase. Grinds with heels up but stable – pivoting on feet for rotation but well balanced, with head still.
	Backward (++): Balls of feet by front of pedestal, low body position with knees at ~120°. Gets good rotation around the midline but minimal anterior-posterior movement and a stable head.
Sailor 2	*Forward (=):* Stands over the pedestal, pushing down. Heels up with lateral weight shift between feet. Head and trunk are stable.
	Backward (++): Most upright of all the sailors examined. Balls of feet by the front of the pedestal with knees at 130-140°. Large rotation at the hips/shoulders while still holding a stable anterior-posterior position.
Sailor 3	*Forward (-):* Right side dominant. Anterior-posterior movement of trunk and especially head. Stands with heels up and quite a lot of movement of the feet during trial – not stable base.
	Backward (--): Low position with knees at ~120°. Feet quite far forward (instep at pedestal) and move a lot. Very unstable head, shoulder, hips, with transverse rotation, lateral tilt, anterior-posterior movement.
Sailor 4	*Forward (--):* Unusual as trunk and head are stable but performs below strength. Flat foot stance which may limit rotation at hips/shoulders.

	Backward (--): Again unusual as has good stability but performs below strength. Balls of feet by pedestal but knees ~130° so more upright than most. Not a lot of rotation and looks cramped in pull phase.
Sailor 5	*Forward (--):* Stands reasonably far back from pedestal with flat feet and seems to slip when pushing hard (jerky circles). Quite a bit of anterior-posterior head and trunk movement.
	Backward (++): Low position. Stands quite far back with toes by front of pedestal and knees ~120°. Stable trunk, with hips and shoulders staying level but opening up well through rotation.
Sailor 6	*Forward (-):* Stable base (stands with heels up but not too much foot movement) but quite a lot of anterior-posterior trunk movement.
	Backward (=): Toes/balls of feet at front of pedestal with knees ~120°. Lots of anterior-posterior trunk movement but fairly balanced. Large forward trunk lean which appears to cramp up the pull phase.
Sailor 7	*Forward (+):* Good rotation with stable trunk and little head movement. Stands quite close/above the pedestal, pushing down.
	Backward (=): Low position with balls/instep of feet by front of pedestal and knees ~120°. Good rotation with head fairly still and shoulders and hips staying level, although gets a bit messy with fatigue.
Sailor 8	*Forward (+):* Stands with flat feet and a stable lower body but also anterior-posterior trunk movement, which makes him an exception as he still performs above strength.
	Backward (-): Upright stance with feet quite a way forward (ankles at pedestal) and knees at ~130°. Anterior posterior trunk movement.
Sailor 9	*Forward (=):* Stable head and trunk with rotation but minimal anterior-posterior movement. Stands with heels up.
	Backward (+): Toes at pedestal and knees ~120°. Good rotation with head stationary and hips and shoulders stay level.
Sailor 10	*Forward (+):* Stands a long way back, up on toes with a lot of foot and lower limb movement, however the trunk and head remain stable.
	Backward (=): Balls of feet at pedestal and knees ~120°. Head is stationary with transverse rotation of trunk while shoulders and hips remain level.

CONCLUSIONS

There are a number of patterns that have emerged from this analysis that tend to distinguish between "good" and "poor" grinders from a technique point of view. It is important to note that while there may be exceptions; these characteristics will influence performance for the majority of individuals.

Forward grinding:

- Force should be applied as evenly as possible throughout the whole cycle. While there are certain phases in which more force can be applied, concentrate on trying to maintain the pressure on the handles and grinding in circles as much as possible.
- Balance and trunk stability should be maintained as much as possible. Rotation at the hips and shoulders is an essential part of grinding, but the midline of the trunk should remain fairly stationary, resulting in less energy wastage and better maintenance of balance.

Backward grinding:

- Pulling strongly and generating power across the top of the crank arm rotation is the key phase of backward grinding in terms of performance. Pushing through the underside of the rotation is also beneficial in terms of maintaining momentum of the handles, but not as crucial as the pull across the top.
- Balance and trunk stability. As with forward grinding, maintaining trunk position provides a better platform from which to base the grinding movement. Keeping a balanced position will allow repeated powerful pull phases across the top, rather than a good one and then a period of imbalance and adjustment.
- Low body position. Keeping knees bent and getting lower will result in a stronger position for the key pull phase across the top of the crank arm rotation. However, stability should not be sacrificed when doing this so it is important to keep foot position and distance from the pedestal balanced.

APPENDIX 4: BIOMECHANICAL CHARACTERISTICS OF GRINDING IN AMERICA'S CUP SAILING

Pearson SN, Hume PA, Cronin JB, Slyfield D. Biomechanical characteristics of grinding in America's Cup sailing. In: Harrison D, Anderson R, Kenny I, editors. XXVII International Conference on Biomechanics in Sports Proceedings; 2009 17-21 August; University of Limerick, Limerick, Ireland; 2009. p. 694.

INTRODUCTION

Understanding the biomechanics of a sporting movement and what aspects of the movement technique most influence performance can facilitate more specific training, both in terms of strength and conditioning and technical improvements. This study was undertaken to describe the kinetic, kinematic, and muscular activation characteristics of the grinding movement in America's Cup sailing, a high intensity constrained cyclic movement (similar to bicycling) performed with the upper limbs.

METHODS

Ten male America's Cup sailors (33.6±5.7 years, 97.9±13.4 kg, 186.6±7.4 cm) who performed grinding regularly as part of their on-board role participated in this study.

Each sailor performed eight maximal grinding performance tests, of eight-second duration, on a custom-built grinding simulator (Dynapack, New Zealand). Performance tests were conducted under four conditions: forward and backward grinding at both moderate and heavy loads, with two tests completed for each condition (eight tests in total). In addition to power output from the grinding simulator, which was used as a performance measure, the following biomechanical data was also collected:

- Full body (nine segment) 2D sagittal plane kinematics, digitised using APAS (Ariel Dynamics, USA).
- Torque-angle analysis from the grinding handles using an adapted SRM system with torque analysis module (SRM, Germany).
- EMG (Bortec AMT-8 system; Bortec, Canada) on seven upper body sites.

RESULTS

Analysis of all data has yet to be completed; however, findings from preliminary results are as follows:

- Peak torque application typically occurs through 60-200° for forward grinding and 300-40° for backward grinding (0° = crank handle vertically upwards).
- Shoulder angles at peak torque were similar for forward and backward grinding, at 83.5±10.3° and 83.0±7.1° respectively.
- Variation in torque application throughout the grinding cycle was negatively associated with forward grinding performance (r = -0.60; lower 90% CL = -0.88, upper 90% CL = -

0.02) but positively associated with backward grinding performance (r = 0.48; CL = -0.15, 0.83).

DISCUSSION

Although results are not yet complete and currently inconclusive, preliminary results do indicate areas in which adaptations to aid performance enhancement may be implemented. One potential area is that the stimulus during strength training could be altered to more specifically target the key joint angles relating to torque production in grinding, in particular for backward grinding where it appears that the majority of work is performed through specific sectors of the cycle. In contrast, the negative association between variability of torque application and forward grinding performance could mean that technical adaptations to maintain consistent handle force through the cycle may be beneficial.

APPENDIX 5: KINEMATICS AND KINETICS OF THE BENCH PRESS AND BENCH PULL EXERCISES IN A STRENGTH-TRAINED SPORTING POPULATION

Pearson SN, Cronin JB, Hume PA, Slyfield D. Kinematics and kinetics of the bench press and bench pull exercises in a strength-trained sporting population. In: Menzel H-J, Chagas MH, editors. XXV International Symposium on Biomechanics in Sports Proceedings; 2007 23-27 August; Federal University of the State of Minas Gerais in Belo Horizonte, Ouro Preto, Brazil; 2007. p. 470-3.

OVERVIEW

A comparison of kinematics and kinetics from the upper body musculature in shoulder flexion (bench press) and extension (bench pull) movements were performed across loads of 10-100%1RM. Twelve elite male sailors with extensive strength-training experience participated in the study. 1RM strength and force were greater in the bench press, while velocity and power output were greater for the bench pull across the range of loads. P_{max} for both mean and peak power occurred at a significantly ($p<0.000$) higher relative load in the bench pull (78.6±5.7% and 70.4±5.4% of 1RM) than the bench press (53.3±1.7% and 49.7±4.4% of 1RM). Findings can most likely be attributed to differences in muscle architecture for shoulder extension/pull and flexion/push movements, which may have training implications for these muscles.

INTRODUCTION

Muscular power, as the combination between force and velocity, has been identified as an important factor in the performance of many sporting activities. Resistance training plays an important role in the development of muscular power, although there is still considerable conjecture in the literature as to the most efficient method of developing power [58]. In order to understand how muscular power can best be developed, it is important to understand how load influences power output. The load that maximizes muscular power output (P_{max}) is one variable, which is considered important in improving the performance of various sporting movements. However, Cronin and Sleivert [59] identified a number of issues within the current available research in this area and the generalization of results, given the variation in P_{max} load across populations and movements.

While extensive research on the power-load spectrum has been conducted with the bench press exercise using different populations, there has been very little examination of other upper body exercises/movements. Therefore, the aim of this study was to compare characteristics of the power-load spectrum of an upper body shoulder horizontal flexion/push movement (bench press) with an extension/pull movement (bench pull/prone row) in a strength trained, sporting population. Although it has received little research attention the bench pull is another key multi-articular exercise used in the conditioning of athletes across a wide variety of sports, and as such a better understanding of the kinetic and kinematic characteristics of this movement will be of benefit to the neuromuscular development of athletes.

METHODS

Participants: Twelve elite-level sailors from the Emirates Team New Zealand America's Cup syndicate participated in this study. The sailor's mean (± SD) age, body mass, and height were 33.9 ± 5.5 years, 97.8 ± 12.5 kg, and 186.0 ± 7.1 cm. All participants had an extensive strength-training background (minimum of 3 years) and the bench press and bench pull exercises were commonly used as part of their training program. During routine strength testing performed in the week immediately prior to this study, mean (± SD) 1RM strength scores for the bench press and bench pull were calculated as 140.9 ± 26.6 kg and 120.6 ± 16.9 kg respectively, using the prediction equation of Mayhew et al. [91].

Equipment: Testing was performed on a modified Smith machine (Figure 1). A linear transducer (Unimeasure, Oregon) was attached to the bar and measured bar displacement with an accuracy of 0.1 mm. These data were sampled at 500 Hz and relayed to a Labview based acquisition and analysis program.

Figure 1: Testing set-up for the power-load spectrum of the bench pull exercise.

Procedures: Each participant completed a 60-minute testing session involving both the bench press and bench pull exercises (Figure 2). Familiarisation was conducted through a self-determined, exercise-specific warm-up typically consisting of 3-4 warm-up sets of the particular exercise using progressively heavier loads. Following the warm-up the individuals' 1RM (Smith machine, concentric-only) was determined to the nearest 2.5 kg. Load for the power profile was then determined from 10-100% of 1RM at 10% intervals. Single repetitions of each load were performed in ascending order, with the instruction that each lift should be performed as explosively as possible. All lifts were separated by a rest period of 1-2 minutes and were concentric-only, with the bench press initiated from mechanical stops positioned ~3 cm off the sailor's chest, and the bench pull initiated from a supported supine position.

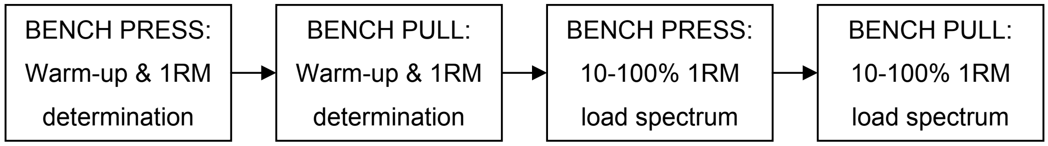


Figure 2: Structure of the testing session.

Data and statistical analyses: Displacement-time data were filtered using a low pass Butterwoth filter with a cutoff frequency of 6 Hz, then differentiated to determine instantaneous velocity, acceleration, force and power output data over the range of motion for each load condition. Descriptive statistics for all variables are represented as mean and standard deviations. P_{max} values and power drop-off around P_{max} were calculated using the line estimation function (least squares method) in Microsoft Excel. Presence of significant systematic discrepancy between measures from the bench press and bench pull was determined using a two-tailed unpaired *t*-test (α level of $p \leq 0.01$).

RESULTS

Set-up specific determination of 1RM performance resulted in mean 1RM scores of 119.7±23.9 kg for the bench press and 99.4±15.4 kg for the bench pull. Table 1 displays the force, velocity, and power output values for the bench press and bench pull across the range of relative loads. It is notable that force values were higher for the bench press/flexion movement while velocity values were greater for the bench pull/extension movement. In addition, while both movements followed the typical force-velocity trade-off, the patterns of how these characteristics related to each other differed. Force values maintained a linear relationship throughout the range of loads; with force values for the bench pull approximately 17% lower relative to the comparative force values of the bench press. However, when bench pull velocity values were expressed relative to comparative bench press velocities they increased in an exponential manner as relative load increased (Table 1), with the mean velocity for the concentric phase of the bench pull over 500% greater than for the bench press at the 1RM load (100% 1RM).

Power output was at a similar level for the two movements at low load (10% 1RM), but a substantially greater increase was observed with increased load for the bench pull in comparison to the bench press. It was also noticeable that mean power output was maximised at a significantly higher load ($p<0.001$) for the bench pull (78.6±5.7%1RM) than the bench press (53.3±1.7%1RM). Similar values were found for the peak power, although the relative load at which maximum values occurred appeared to be slightly lower for both the bench pull (70.4±5.4%) and bench press (49.7±4.4%). In addition, reduction in power output either side of P_{max} was significantly lower ($p<0.001$) for the bench pull at both 10% and 20% of load away from P_{max}, with a power output drop-off of 1.6% and 6.5% for the bench pull and 3.2% and 12.9% for the bench press.

Table 1. Kinematic and kinetic measures (mean±SD) for the bench press and bench pull exercises throughout a range of loads (%1RM).

Load	Bench Press			Bench Pull		
(%1RM)	Velocity (m/s)	Force (N)	Power (W)	Velocity (m/s)	Force (N)	Power (W)
10%	0.95±0.14	122±29	117±36	1.20±0.16	102±15	125±32
20%	0.85±0.15	234±49	199±61	1.17±0.14	198±31	235±63
30%	0.72±0.10	354±70	253±57	1.06±0.12	293±45	315±80
40%	0.61±0.10	473±96	286±65	0.99±0.07	389±64	387±82
50%	0.52±0.10	592±124	306±75	0.88±0.05	488±75	432±82
60%	0.44±0.09	708±146	303±64	0.79±0.06	573±87	454±89
70%	0.34±0.05	829±167	284±64	0.73±0.04	685±103	499±88
80%	0.24±0.05	942±187	225±55	0.65±0.05	779±119	506±86
90%	0.15±0.04	1049±216	153±50	0.53±0.04	878±131	468±80
100%	0.09±0.03	1176±232	105±38	0.47±0.03	984±147	462±78

Note: Measurements are the mean value of the sample for the concentric phase of a single repetition.

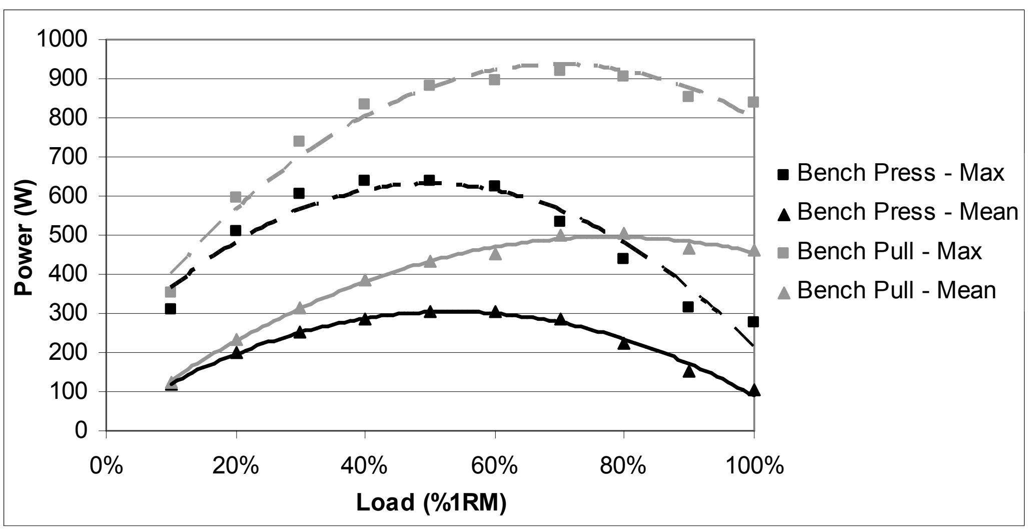


Figure 3: Comparison of the power-load spectrum for the bench press and bench pull. Curves are presented for both mean and maximum power from a single, averaged (all sailors), repetition.

DISCUSSION

The most notable finding of this study was the divergent power-load spectrum profiles of the bench press and bench pull. Muscular power output was higher for the bench pull throughout the entire load range, and significantly ($p<0.01$) so at loads of 40%1RM and greater which was interesting given the higher loads (~17%) being lifted in the bench press at the same relative load. Given that power is the product of force and velocity it would seem that the combination of these two variables is dependent on the muscles/movement used as evidenced in this agonist-antagonist pairing. That is, the greater velocities and subsequent power outputs observed in the bench pull movement may be attributed to the differing muscle architecture. The greater fibre lengths and longitudinal fibre arrangement of the primary movers in the bench pull exercise (latissimus dorsi, biceps brachii, brachialis) are characterised by faster shortening velocities, whereas the primary movers for the bench press (pectoralis major, triceps brachii) have shorter fibre lengths, greater pennation angles, and subsequently greater force capability. In terms of power output, it is evident that the benefits gained from the greater velocity-generating capability of the musculature used in the bench pull greatly out-weighed the corresponding deficit in force, especially as relative load increased.

These differences in muscular characteristics also resulted in a significant difference ($p<0.001$) in the relative load at which P_{max} occured. P_{max} loads for the bench press of around 50%1RM for both mean and peak power, along with a power output drop-off of ~3% for a 10% variation in load, means these findings were consistent with previous comparative research, which have reported P_{max} loads of 30-60%1RM [58, 75]. In contrast, P_{max} occurred at a much heavier load for the bench pull – 78.6%1RM for mean power and 70.4% for peak power. Similar findings have been reported in-situ for a single muscle fibre, with Edgerton et al. [79] attributing the differences observed between power outputs and P_{max} loads in muscle groups of the lower limb to differences in muscle architecture (fibre length, type and arrangement). While Edgerton et al. [79] reported flexor P_{max} to occur at a higher relative load (59%) than extensor P_{max} at the knee, the higher values again corresponded with the action involving more fusiform muscles with greater fibre length.

CONCLUSIONS

The force, velocity, and power generating characteristics for the shoulder extensor muscles (bench pull) were substantially different from the shoulder flexors (bench press). The bench pull produced greater velocities and power outputs, along with exhibiting a higher relative load for P_{max} – findings which may be due to differences in muscle architecture. This may have implications in terms of the way different muscle groups or movement patterns are trained, depending on the requirements of the activity of interest.

APPENDIX 6: BENCH PRESS VERSUS BENCH PULL – KINEMATICS, KINETICS AND 1RM DETERMINATION

Pearson SN, Cronin JB, Hume PA, Slyfield D. Bench press versus bench pull – kinematics, kinetics and 1RM determination. Sports Medicine and Sport Science and Exercise Science New Zealand Conference; 2007 November Hamilton; 2007. p. 74.

BACKGROUND

Muscular strength and power have both been identified as an important factor in the performance of many sporting activities. This paper examines how load and movement type influences power output in two key strength training exercises, and addresses the accuracy of equations for predicting 1 repetition maximum (1RM) – the standard measure of assessing strength [92] – when used in different exercise conditions.

METHODS

Twelve elite-level sailors with extensive strength-training experience participated in this study (body mass 97.8±12.5 kg, height 186.0±7.1 cm). Testing was performed on a Smith machine instrumented with a linear transducer which measured bar displacement with an accuracy of 0.1 mm. Testing sessions were 60-minutes and involved both the bench press and bench pull exercises. 1RM strength was calculated from training data using prediction equations[93], in addition to actual 1RM's determined to the nearest 2.5 kg. Power testing was conducted using loads of 10-100% of actual 1RM at 10% intervals. Single repetitions of each load were performed in ascending order, with the instruction that each lift should be performed as explosively as possible.

RESULTS AND DISCUSSION

1RM was significantly ($p<0.001$) over-estimated by the prediction equation for both bench press and bench pull, with the divergence of the calculated 1RM from the determined 1RM significantly greater ($p=0.036$) for the bench pull.

Comparison of kinetic and kinematic variables across the 10-100% 1RM load spectrum showed higher force values for the bench press while velocity values were greater for the bench pull. While power output was at a similar level for the two movements at low load (10% 1RM), significantly greater power outputs were observed for the bench pull in comparison to the bench press with increased load. It was also noticeable that mean power output was maximised at a significantly higher load ($p<0.001$) for the bench pull (78.6±5.7%1RM) than the bench press (53.3±1.7%1RM).

CONCLUSIONS

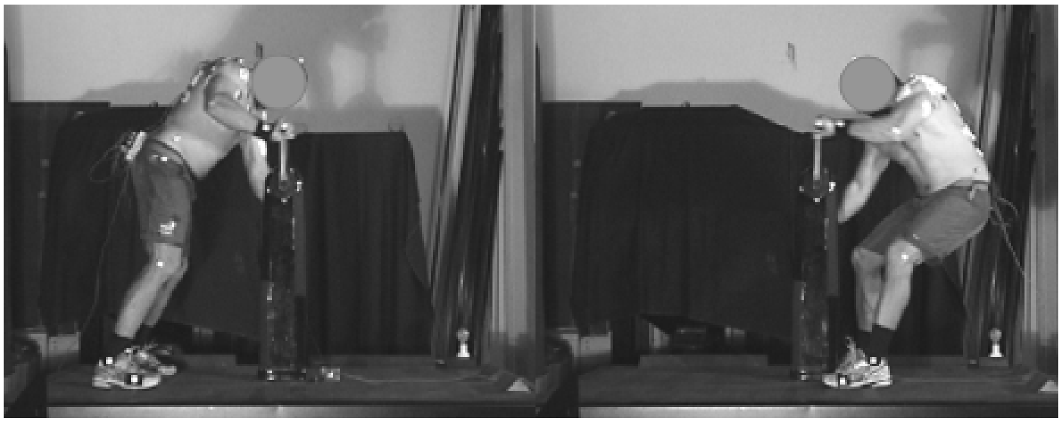
Force, velocity, and power characteristics for the shoulder extensor muscles (bench pull) were substantially different from the flexors (bench press). Bench pull produced greater velocities and power outputs, along with exhibiting a higher relative load for P_{max} – a finding which may have training implications and which is possibly due to differences in muscle architecture.

Prediction equations for 1RM should, as much as possible, be specific for the movement and contraction type being performed. Alternatively, awareness of the limitations of the equation(s) used and possible correction factors may help to avoid miscalculation in terms of exercise and load prescription.

APPENDIX 7: RESULTS OF POWER THE PROFILING STUDY

Pearson SN, Cronin JB, Hume PA. Results of power the profiling study. Technical report to Emirates Team New Zealand. Auckland, NZ: Institute of Sport and Recreation Research New Zealand, Auckland University of Technology; 2006 May 2006. 6 pages.

Results of the power profiling study



A technical report for Emirates Team New Zealand

May 2006

Prepared by:
Simon Pearson, Associate Professor Patria Hume, Associate Professor John Cronin
Institute of Sport and Recreation Research New Zealand,
Division of Sport and Recreation, Auckland University of Technology

Reviewed by David Slyfield
Emirates Team New Zealand

AUCKLAND UNIVERSITY OF TECHNOLOGY
TE WĀNANGA ARONUI O TAMAKI MAKAU RAU

AIM

There were two main purposes for analysis of kinematic and kinetic information for the bench press and bench pull exercises:

- Determine force-velocity-power profiles of elite grinders using exercises that they use in training e.g. bench press and bench pull.
- Determine the relationship between these profiles and other kinematic and kinetic variables, and grinding performance.

METHODS

During the end of February and start of March we obtained kinematic and kinetic information for the bench press and bench pull exercises, using 11 Emirates Team New Zealand sailors. Testing was conducted using an instrumented Smith machine. Concentric-only, explosive, single repetitions were performed at 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100% of each individual's 1RM for both bench press and pull.

RESULTS AND DISCUSSION

Power profiles of elite America's cup sailors (bench press, bench pull)

There an increasing body of research into the weight-training loads that maximise power output (Pmax), due to the importance of power (the combination of force and velocity) to many sporting movements. Identifying the loads at which Pmax occurs could theoretically provide useful information for helping optimise weights-based training for sporting activities.

General Findings: Using grouped data, a marked difference at where peak mean power occurred for bench press and bench pull was observed. Peak extension power (bench press) occurred at 53% of 1RM while peak flexion power (bench pull) occurred at 77% of 1RM. A large amount of previous research using bench press has reported similar values to this study, with peak mean power occurring between 40-60% 1RM. While there has been much less research into upper body flexion exercises, what results there are have also tended to support our finding of peak mean power occurring at a higher %1RM.

I have done a brief comparison of peak power values from our study to those from other studies using bench press. Within these studies there are a range of protocols used, many of which include rebound (SSC) bench press and bench press throws, both of which substantially increase power output and are therefore not comparable with our data. One study using the same concentric only, bench press protocol and a roughly comparable population did not report the entire spectrum of loads that we used but came up with similar values at the 60%1RM load (approximately Pmax).

	Participants	1RM	Power @ 60%1RM
Cronin (2000)	9	101±7.2	315±62.0
ETNZ (2006)*	10	119±25.1	316±52.7

* One sailor was left out of this data

However there are some differences between the two groups that are worth noting. Firstly, while Cronin (2000) study used an athletic population, they had not used strength training in 6 months prior to the study, which (along with the greater average strength of the ETNZ group) would mean the ETNZ sailors could be expected to perform better in terms of power values, which does not seem to be the case. Looking more closely at the data it shows that the reason for this is that while the ETNZ sailors are stronger and better at applying force (one of the components of power), they do not have the same ability as the other group to develop velocity, the other component necessary to generate power. This is probably fairly consistent with training background and task requirements. While maximal strength is generally more of a commodity than speed in a sailing/grinding setting (a point that comes up again later), most of the athletes from the other study were rugby players – a sport in which movement velocity and power (speed of force application) are more critical.

Predicting grinding performance

1RM scores: As actual 1RM scores were determined for this study in addition to having the equation-predicted 1RM's from strength testing we decided to compare the two and their relationship to grinding performance.

The 1RM's from the study are understandably lower than the predicted strength testing values as they were concentric only, on a Smith machine (restricted motion), compared to a free weight, rebound bench press/pull. However, it was noticeable that
the formula under-predicts more for the bench pull than the press, with the Smith bench pull 1RM (17.1%) significantly lower than the Smith bench press 1RM (14.4%) when compared to their predicted 1RM equivalents. This discrepancy appears to be because the prediction equation was formulated predominantly with the bench press in mind and therefore does not work so well on other movements due to differences muscle fibre arrangement, type, etc. Other studies using the same prediction equation (Mayhew et al, 1992) also support this theory, as the equation has been found to predict bench press the best out of the three powerlifting lifts (followed by squat then deadlift), and predict bench press (4.3% from actual, r=0.901) closer than lateral row (5.1% from actual, r=0.852).

Consistent with these observations, the 1RM scores determined in the study were better predictors of grinding performance than the equation-predicted 1RM's from strength testing. This applied to all grinding conditions (forward and back, medium and heavy loads) but was more pronounced in the backward grinding/bench pull relationship. Likely reasons for the difference in predictive power are:

- Values were determined rather than predicted, giving a better indication of actual strength.
- Being concentric-only rather than rebound exercises the 1RM from the study more closely resembled grinding-specific strength because in grinding (as a cyclic movement) there will be little or no stretch-shorten cycle potentiation of the movement. This is likely to be more applicable to the bench press than the bench pull.
- The prediction equation was formulated for bench press rather than bench pull (as above), meaning that bench pull will not be as well predicted and the relationship with backward grinding reduced.

Because of the stronger relationship with grinding performance, "1RM" throughout the rest of this section refers to the study value.

Best predictors: Bench press 1RM and force are easily the two strongest predictors of forward grinding performance, with the relationship improving as grinding load increases. In the linear regression model used for this data, 1RM and force together explained 87% of the inter-sailor variation in forward medium load grinding, while 1RM by itself explained 97% of the variation in forward heavy load grinding. This shows that maximal strength, rather than power, is the more important muscular characteristic for forward grinding performance. While power had moderate correlations (r=0.500-0.550), the ability to generate velocity in the bench press showed virtually no relationship with forward grinding performance.

For backward grinding and bench press, the maximal strength variables (1RM, force) still had very strong relationships with grinding performance, however, the ability to generate power and velocity seems to be much more important. While 1RM is still the best predictor of medium load backward grinding performance (explaining 80% of inter-sailor variation), the relationship for power is not far behind (correlation of r=0.815 for power versus r=0.905 for 1RM). Furthermore, for heavy load backward grinding, both maximum velocity (r=0.971) and power (0.957) actually have slightly stronger relationships with performance than 1RM or force (r=0.948 for both). This also shows up in the regression model where max velocity explains 93% of inter-sailor performance variation by itself, and when combined with body mass[2] explains 99.6% of performance variation. However, it should be noted that their were only 6 sailors in the heavy load grinding group, and lower numbers tend to decrease the precision of statistical analyses and increase the likelihood of unusual findings. The graph below shows that while there is

---

[2] When variables are related the influence of the "weaker" variable will be reduced because of the variance it shares with the variable already included in the model. In this case the influence of power, force, and 1RM were sufficiently affected by their shared variance with velocity that body mass (r=0.908) became the second strongest predictor in terms of the model.

definitely a strong relationship between velocity and heavy load backward grinding at the lower bench pull loads, power and force have much stronger relationships throughout the majority of the load spectrum, casting some doubt over the prominence of velocity in the model.

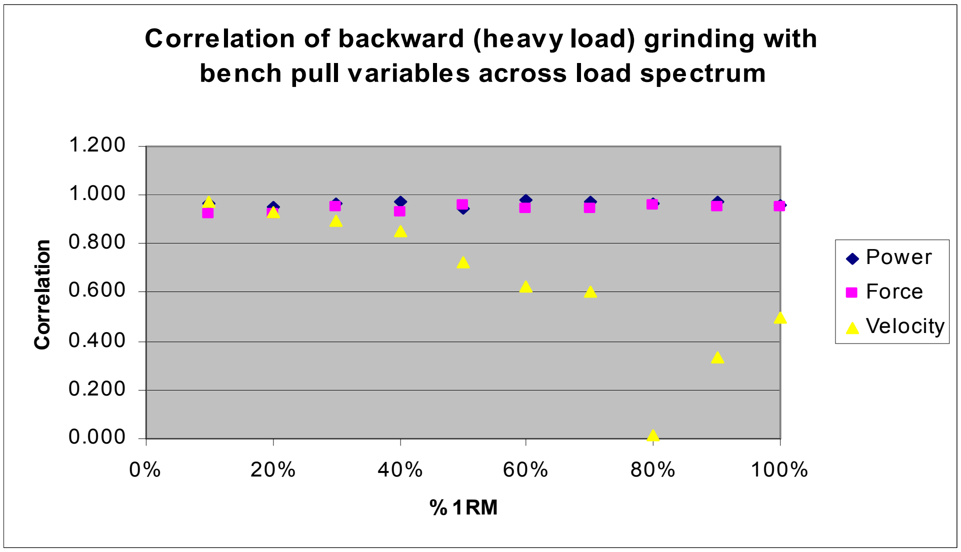


Figure 1: Correlation of backward grinding with bench pull variables across load spectrum.

What is cannot be discounted is that power (and to a lesser extent velocity) has been shown to be an important factor in backward grinding performance, where it was fairly negligible in forward grinding. A likely explanation for this finding is the difference in muscle architecture (fibre length, type, arrangement, etc) between the flexor muscles used for the bench pull and the extensor muscles (bench press). As the flexors tend to have longer fibres running parallel to the line of force generation they are better suited for generating higher contraction velocities. A more "balanced" relationship between force and velocity in the flexor muscles should make the upper body flexion movement inherently more power than force oriented (as opposed to the predominantly force generating extensors). This theory would appear to be consistent with the higher flexor power outputs seen here, along with Pmax for bench pull occurring at a higher percentage of 1RM than for bench press.

What this finding does suggest is that there is probably merit in training the push and pull components of grinding differently, e.g. push/extension could be trained for force generation, while pull/flexion might be trained for power. Another possibility is that conditioning could use an integrated approach that concentrates on both the force and velocity capability of muscle, with certain emphases for different individuals as diagnosed by these tests. However, using such analysis might be of better diagnostic value if normative data can be generated with greater subject numbers.

APPENDIX 8: BACKWARD GRINDING PERFORMANCE AND REP TEMPO IN WEIGHT TRAINING

Pearson SN, Cronin JB, Hume PA. Backward grinding performance and rep tempo in weight training. A technical report for Emirates Team New Zealand: Institute of Sport and Recreation Research New Zealand, Auckland University of Technology; 2007 June. 8 pages.

Backward grinding performance and rep tempo in weight training

A technical report for Emirates Team New Zealand

January 2007

Prepared by:
Simon Pearson[1], Associate Professor John Cronin[2], Associate Professor Patria Hume[1]
[1]Institute of Sport and Recreation Research New Zealand, Division of Sport and Recreation, Auckland University of Technology
[2]School of Exercise, Biomedical and Health Sciences, Edith Cowan University

KEY POINTS

Aim of the report

To outline the findings of a training intervention designed to investigate the effect of different training velocities in pull-based resistance exercises on backward grinding performance.

Method of data collection

Fourteen sailors were divided into two groups, a strength training (control) group and a power training (experimental) group, for a six-week training intervention. The intervention involved the manipulation of concentric phase tempo for all exercises involving shoulder extension/pull-based movements, with the experimental group performing this phase as quickly as possible, while the control group performed a controlled velocity movement. Movement speed was the only difference in training stimulus as loads lifted were consistent between groups.

Both immediately pre- and post-intervention the sailors performed a maximal strength (1RM) bench pull, a backward grinding performance test, and an incremental power profile test on the bench pull exercise.

Practical implications of the report

Explosive/power-focussed training was successful in improving muscular performance characteristics such as power, velocity of movement, and rate of force development in the bench pull movement to a greater extent than conventional, controlled-lifting training. Changes in these variables were also the most closely related to and predictive of the changes observed in grinding performance over the course of the six-week intervention period.

Performance changes following the intervention period were greater for the experimental group than the control group. While the results were not conclusive given the small number of grinders and hence statistical limitations, there is likelihood (greater for heavier loads) that the experimental training methods are beneficial (22-52%) to backward grinding performance and very little possibility (0-5%) that training in this manner will impede performance.

Next steps

It is recommended that the explosive lifting for pull-based weight-training exercises used by the experimental group should be adopted for all sailors involved in grinding as part of the periodised training program of grinders.

INTRODUCTION

During February-March 2006 testing was performed examining the relationship between muscular performance characteristics and grinding performance. Forward grinding performance was best predicted by maximal strength variables (bench press 1RM, mean force), which was very much in concurrence with the type of weights training being employed with the grinding sailors. However, for backward grinding, while the maximal strength variables (bench pull 1RM, force) still had very strong relationships with grinding performance, the ability to generate power (moving high loads quickly) appeared to be more important.

While (bench pull) 1RM was still the best predictor of medium load backward grinding performance, the relationship for power was similar (correlation of r=0.82 for power versus r=0.905 for 1RM). Furthermore, for heavy load backward grinding, both velocity (r=0.971) and power (0.957) had slightly stronger relationships with performance than 1RM or force (r=0.948 for both). A possible explanation for this finding is the difference in muscle architecture (fibre length, type, arrangement, etc) between the flexor muscles used for the bench pull and the extensor muscles (bench press). As the flexors tend to have longer fibres running parallel to the line of force generation they are better suited for generating higher movement velocities. A more “balanced” relationship between force and velocity in the flexor muscles should make the upper body flexion movement inherently more power than force oriented – a theory consistent with the higher power outputs and Pmax % seen in the bench pull compared to the bench press. Consequently, there may be merit in training the push and pull components of grinding differently. While the research has supported the continued training of the push/extension movement (associated with forward grinding) for force generation, there may be benefit in pursuing a more power-oriented training focus with the pull/flexion movement associated with backward grinding. The present experiment was therefore devised with the aim of determining the effect of power-based weight training on backward grinding performance.

METHODS

Participants

Fourteen Emirates Team New Zealand sailors who performed grinding as part of their on-board role participated in this study. For the purposes of the intervention the sailors were divided into two training groups, an experimental group and a control group. Groups were matched, as much as possible, for pre-intervention strength, backward grinding performance and body mass, as well as sailing role.

Table 1. Pre-intervention subject characteristics of the two training groups (mean±SD).

	Body Mass (kg)	1RM Bench Pull (kg)[1]	Grinding performance (J)[2]
Control (n = 7)	98.2±14.0	113.1±21.2	92204±10278
Experimental (n = 7)	97.9±15.9	114.4±19.5	91283±13349
Difference (%)	***-0.3%***	***1.1%***	***-1.0%***
raw units	*-0.3*	*1.3*	*-921*

[1] Predicted 1RM determined during routine strength testing.

[2] Backward grinding performance at the highest load completed by all participating sailors (48 N m).

Testing procedures

All fourteen sailors were tested for backward grinding performance and bench pull performance twice; Firstly in the week immediately preceding the training intervention and secondly in the week immediately following the completion on the intervention. At the time of pre-testing the sailors were not aware of which training group they would be allocated to.

Grinding performance

Backward grinding performance was assessed using two loading conditions, designated as *Moderate* (48 N m) and *Heavy* (68 N m). Due to the strength requirements for performing the *Heavy* condition, only eight sailors (four from each group) completed the test at this load.

Testing was conducted on a grinding simulator in a manner familiar to the sailors, as the protocol was the same as for grinding testing performed regularly as part of their fitness monitoring. At each testing load a sailor would perform three maximal-effort grinds of eight-seconds separated by a rest period of a minimum of two minutes. The performance measure of interest was the total work (J) performed during a five-second period from peak power (see Figure 1). Total work was determined for each trial, and the three-trial mean used as the performance measure.

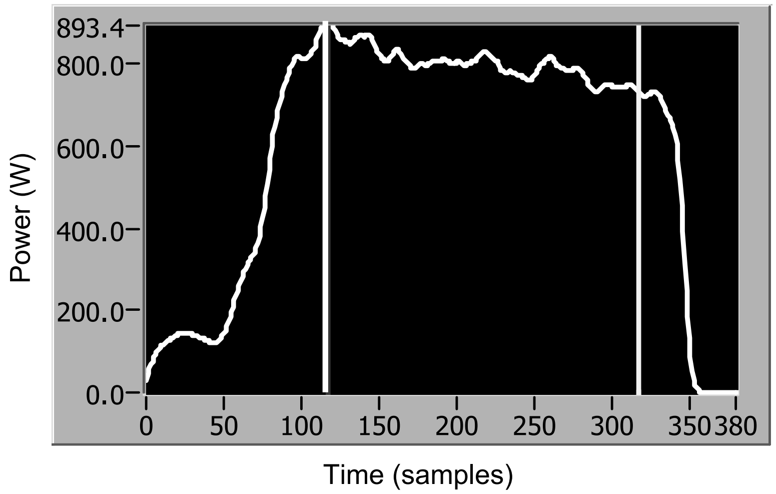


Figure 1: An example power output trace from a complete trial. Vertical markers indicate peak power, and five seconds post peak power.

Bench pull power profiles

Various measures of muscular ability in a shoulder extension movement were determined using a bench pull motion on an instrumented Smith machine. Following an incremental warm-up, a set-up specific bench pull 1RM was determined for each sailor. With suitable rest between lifts, sailors then performed a single maximal repetition at loads of 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100% of 1RM, with loads presented sequentially from lightest to heaviest. From these lifts we were able to calculate forces, velocities, and power outputs at each load in addition to spectrum information such as the %1RM at which maximum power output (Pmax) occurred.

Intervention

Sailors completed a six-week training intervention period. Weight training programmes across all participating sailors were of a standardised structure (see Table 2). Although there was some variation in specific exercises performed according to sailing role, bench pull was common to all programmes.

Table 2. Weight-training loading structure for the six-week intervention period.

Weeks	Reps	Work sets
1-2	8-10	3 sets, short rest
3-4	5-7	3 sets, moderate rest
5-6	3-4	2 sets, long rest

The only substantial difference between the training groups was the instruction given on how exercises should be performed. Sailors in the experimental group were instructed to perform their shoulder extensor/pull exercises explosively, moving the loads as quickly as possible through the concentric phase. In contrast, the control group were told to perform these movements as they would in their normal/conventional training, with the concentric phase at a controlled, steady pace. By limiting the difference in the training stimulus to purely the temporal characteristics of the lifts, the influence of confounding factors such as differences in volume and intensity will have been negated.

RESULTS AND DISCUSSION

Alteration of muscular performance characteristics

Examining the changes in muscular performance characteristics in the two groups following the training intervention, it appears that the different training methods were successful in altering muscular performance characteristics in accordance with their intent. Table 3 shows the changes in all the strength variables measured. It is noticeable that variables such as velocity, time to max force and power improved more in the experimental group while variables such as force improved more in the control group – results consistent with the training stimuli used in each group.

Table 3. Changes in muscular performance characteristics following the intervention.

	Control group (n = 7)	Experimental group (n = 7)	Inter-group difference (p-value)
Gym 1RM Bench Pull[1]	4.8±4.4%	5.1±3.3%	0.916
Smith 1RM Bench Pull	5.2±4.0%	2.6±3.3%	0.215
Velocity (spectrum max)	-0.6±6.3%	8.4±2.6%	0.008
Velocity (at Pmax)	-2.7±6.9%	5.4±8.8%	0.080
Velocity (at 1RM)	0.6±7.2%	8.0±7.1%	0.076
Time to Max Force (max)	10.9±20.3%	-11.1±17.5%	0.051
Time to Max Force (Pmax)	17.0±19.7%	-27.3±48.1%	0.054
Time to Max Force (1RM)	-11.3±39.7%	-34.9±45.7%	0.322
Force (max)	5.4±4.0%	2.5±3.2%	0.174
Force (Pmax)	6.1±5.5%	2.0±3.1%	0.117
IES[2] (max)	-0.3±21.5%	21.6±17.3%	0.058
IES[2] (Pmax)	-21.2±39.0%	6.8±60.5%	0.327
IES[2] (1RM)	7.7±33.1%	19.2±39.6%	0.567
Pmax %	3.7±6.9%	5.7±10.6%	0.698
Power (max)	3.9±5.5%	7.8±4.9%	0.197
Power (1RM)	5.8±8.0%	10.3±8.9%	0.341

[1]Predicted 1RM

[2]IES = Index of explosive strength (max force/time to max force)

Changes in grinding performance

The changes in grinding performance for the two groups following the training intervention period can be observed in Table 4. Both groups exhibited improvements in performance following the intervention period but the differences in changes were not statistically significant. There were greater improvements for the experimental group than the control group in both the moderate and heavy load grinding conditions.

Table 4. Changes in grinding performance following the intervention period.

	Control group (n = 7)	Experimental group (n = 7)	Inter-group difference (p-value)
Moderate load grinding	4.1±2.0%	5.5±2.2%	0.253
Heavy load grinding[1]	10.2±4.7%	13.9±8.5%	0.489

[1] Only 4 sailors from each group

While these results are in no way conclusive, there is a trend that the experimental training intervention was more beneficial for backward grinding performance than the conventional training methods. Further analysis (Table 5) of the performance results indicate that the likelihood of a performance benefit from the experimental training is greater as the grinding load increases. It is also evident that, while there is uncertainty over the positive benefit of the experimental training, there is virtually no chance of a negative effect from this training method. Time and participant limitations of the study may also have impacted on the ability to obtain a clear and conclusive picture of what effect the explosive training may have on grinding performance. In particular, six weeks is a reasonably short time to induce substantial changes in muscular performance characteristics, and while the power profile results (Table 3) show that changes did result from the intervention period, a longer exposure time is likely to have produced more pronounced results.

Table 5. Probabilities of a performance benefit from the experimental training intervention.

	Moderate load grinding performance	Heavy load grinding performance
Likelihood of positive effect	22%	52%
Likelihood of trivial effect	78%	42%
Likelihood of negative effect	0%	5%

Determinants of performance changes

Although the effect on performance is indisputably the key result of the study, it is also useful for our understanding to try and determine what mechanisms were responsible for the observed performance changes. Because the numbers of participants in this study are lower than the desirable amount for linear regression modelling it is necessary to acknowledge that the exact figures produced from the models may be somewhat inaccurate. However, the modelling will provide an indication of the influence of mechanism variables and their approximate contribution to performance change.

Table 6. Predictor model for moderate load grinding performance.

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.614(a)	.377	.325	1.75380
2	.749(b)	.561	.481	1.53807
3	.789(c)	.623	.510	1.49456

a Predictors: power@1RM

b Predictors: power@1RM, velocity(spectrum max)

c Predictors: power@1RM, velocity(spectrum max), velocity@Pmax

Table 7. Predictor model for heavy load grinding performance.

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.886(a)	.785	.749	3.33105
2	.967(b)	.934	.908	2.01902
3	.994(c)	.988	.979	.96696

a Predictors: time-max force@1RM

b Predictors: time-max force@1RM, power@1RM

c Predictors: time-max force@1RM, power@1RM, time-max force(spectrum max)

The model summaries for moderate and heavy load grinding respectively are detailed in Tables 6 and 7. When examining the variables identified in the models as making the greatest contribution to changes in grinding performance it is noticeable that they are exclusively power and speed related variables, with changes in power output at 1RM, rate of force development, and velocity appearing to be the main contributors to predicting performance. These results provide support to the proposed benefits of the velocity-focussed explosive training as the variables identified as having the greatest influence on changing grinding performance were all found to improve more in the experimental group.

It is interesting to note that the one two and three factor models for predicting heavy load grinding performance are substantially stronger than the model for moderate load grinding performance. Although there were more sailors that completed the moderate load condition (n=14 versus n=8 for heavy load), it may be that, with only the stronger and more accomplished grinders completing the heavy load condition, their performance is more consistent and therefore responses are more uniform and more predictable. It may also be due to the stronger relationship between grinding performance and strength as grinding load increases, resulting in better predictive abilities of muscular performance characteristics.

CONCLUSIONS

Although the results of this study were not completely conclusive from a statistical perspective, our findings enable us to conclude the following:

- The experimental training intervention was successful in stimulating different changes in the muscular performance characteristics of Emirates Team New Zealand sailors. Velocity-focussed/explosive training of pull-based exercises was more successful than conventional training for improving the ability of sailors to produce higher power outputs and velocities in the bench pull movement.
- Explosive training resulted in a notably, but not significantly, greater improvement in backward grinding performance than conventional training, over the six-week period. While the evidence of a positive benefit from this training method is not incontrovertible, there certainly appears to be no evidence of a negative effect.
- Muscular performance characteristics that show the greatest relationship with changes in performance were entirely those better stimulated by the experimental training intervention (power output, time to maximum force, velocity). The predictive ability of power/speed variables appears to increase with increasing grinding load.

Based on the combination of evidence it seems reasonable to encourage the use of the power-focussed weight training methods for shoulder extensor/pull-based exercises to be continued and expanded for use with all sailors involved with grinding. The likelihood of a detrimental effect is extremely low, and the evidence for a beneficial effect is encouraging.

APPENDIX 9: SAMPLE OF A PARTICIPANT CONSENT FORM FOR THE KINEMATICS AND KINETICS OF GRINDING STUDY

AUCKLAND UNIVERSITY OF TECHNOLOGY
TE WĀNANGA ARONUI O TAMAKI MAKAU RAU

Consent to Participation in Research

Title of Project:	**Kinematics and kinetics of America's Cup grinding and their role in determining set-up and conditioning practice for improving performance**
Project Supervisor:	**Associate Professor Patria Hume**
Researcher:	**Simon Pearson**

- I have read and understood the information provided about this research project (Information Sheet dated 18th November 2004).
- I have had an opportunity to ask questions and to have them answered.
- I understand that I may withdraw myself or any information that I have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way.
- If I withdraw, I understand that all relevant information will be destroyed.
- I agree to take part in this research.
- I wish to receive a copy of the report from the research: tick one: Yes O No O

Participant signature: ....

Participant name: ....

Date:

Project Supervisor Contact Details:

Associate Professor Patria Hume
NZ Institute of Sport & Recreation Research
Division of Sport and Recreation
Auckland University of Technology
Private Bag 92006
Auckland 1020
Ph 917 9999 ext. 7306
patria.hume@aut.ac.nz

Approved by the Auckland University of Technology Ethics Committee on 06/12/04 AUTEC Reference number 04/221.

APPENDIX 10: SAMPLE OF A PARTICIPANT INFORMATION PACK FOR THE KINEMATICS AND KINETICS OF GRINDING STUDY

AUCKLAND UNIVERSITY OF TECHNOLOGY
TE WĀNANGA ARONUI O TAMAKI MAKAU RAU

Participant Information Sheet

Date Information Sheet Produced: 18th November 2004

Project Title Kinematics and kinetics of America's Cup grinding and their role in determining set-up and conditioning practice for improving performance.

Invitation
You are invited to take part in the above mentioned research project which is the first of several chronologically separate but interlinked studies to be conducted as part of a PhD. Your participation in this testing is voluntary. You are free to withdraw consent and discontinue participation at anytime without influencing any present and/or future involvement with the Auckland University of Technology.
Your consent to participate in this research will be indicated by your signing and dating the consent form. Signing the consent form indicates that you have freely given your consent to participate, and that there has been no coercion or inducement to participate by the researchers from AUT.

What is the purpose of the study?
The aim of this project is to better understand the mechanics of the grinding movement, specifically what muscle groups and joint angles are associated with the development of force/power. This will enable us to investigate ways in which the movements and forces in grinding can be optimised in on-water situations and also how they can be used to make dry-land training more activity-specific to improve grinding performance.

How are people chosen to be asked to be part of the study?
All members of the Team New Zealand sailing crew who are involved in grinding during race conditions are invited to participate in this research

What happens in the study?
Information on the mechanics of grinding will be obtained using surface electromyography electrodes (which feel like a sticking plaster on your skin, and detect when muscles are being activated), video footage, and force/angle information from the instrumented grinding handles. This data will be collected both on-water and using a land-based grinding simulator to help us better understand the grinding movement. Further testing will then be performed on the grinding simulator allowing us to also look at the effect of variables such as deck tilt on grinding performance.

The information gained from these studies will then be used to identify which movements and muscles are responsible for force generation so that we can work out ways to train the muscles better. We will also look to identify whether there are any alterations to technique which could improve performance.

What are the discomforts and risks?
There is a possible injury risk however this is equivalent to what you normally experience during physical training or competition.

What are the benefits?
There is the potential for improvements in grinding performance through a number of methods including more specific dry-land training programs, alterations to grinding pedestal set-up, and technique changes.

How will my privacy be protected?
The identity of individuals will be made available in reports to the Emirates Team New Zealand syndicate, but any information published outside of Emirates Team New Zealand will have

subject identities concealed. In the case of any video footage, subject's faces will be obscured/blanked out. The results of the studies are embargoed until a period after the Emirates Team New Zealand races have finished in the current syndicate.

Participating in this research project will not cost you apart from your time.

Opportunity to receive feedback on results of research
You may ask for a copy of your personal results at any time.

Participant Concerns
If you have any questions please feel free to contact Simon Pearson or Associate Professor Patria Hume. Any concerns regarding the nature of this project should be notified in the first instance to the Project Supervisor – Patria Hume. Concerns regarding the conduct of the research should be notified to the Executive Secretary, AUTEC, Madeline Banda, madeline.banda@aut.ac.nz , 917 9999 ext 8044.

Researcher Contact Details: Simon Pearson, New Zealand Institute of Sport and Recreation Research Division of Sport and Recreation, Auckland University of Technology. Email: simon.pearson@aut.ac.nz or phone +64 9 917 9999 ext 7855.

Project Supervisor Contact Details: Associate Professor Patria Hume, New Zealand Institute of Sport and Recreation Research, Division of Sport and Recreation, Auckland University of Technology. Email: patria.hume@aut.ac.nz or phone +64 9 917 9999 ext 7306.

Approved by the Auckland University of Technology Ethics Committee on 06/12/04 AUTEC Reference number 04/221.

APPENDIX 11: ETHICS APPROVAL FROM AUTEC

AUCKLAND UNIVERSITY OF TECHNOLOGY
TE WĀNANGA ARONUI O TAMAKI MAKAU RAU

MEMORANDUM

Academic Services

To:	Patria Hume
From:	Madeline Banda
Date:	20 December 2004
Subject:	04/221 Kinematics and kinetics of America's Cup grinding and their role in determining setup and conditioning practice for improving performance

Dear Patria

Thank you for providing amendment and clarification of your ethics application as requested by AUTEC.

Your application was approved for a period of two years until 20 December 2006.

You are required to submit the following to AUTEC:

- A brief annual progress report indicating compliance with the ethical approval given.
- A brief statement on the status of the project at the end of the period of approval or on completion of the project, whichever comes sooner.
- A request for renewal of approval if the project has not been completed by the end of the period of approval.

Please note that the Committee grants ethical approval only. If management approval from an institution/organisation is required, it is your responsibility to obtain this.

The Committee wishes you well with your research.

Please include the application number and study title in all correspondence and telephone queries.

Yours sincerely

Madeline Banda
Executive Secretary
AUTEC

cc: Simon Pearson, simon.pearson@aut.ac.nz

APPENDIX 12: ETHICS EXTENSION FROM AUTEC

AUT UNIVERSITY
TE WĀNANGA ARONUI O TAMAKI MAKAU RAU

MEMORANDUM

Academic Services

To:Patria Hume

From:**Madeline Banda** Executive Secretary, AUTEC

Date: 27 November 2006

Subject: Ethics Application Number 04/221 **Kinematics and kinetics of America's Cup grinding and their role in determining setup and conditioning practice for improving performance.**

Dear Patria

I advise that the Auckland University of Technology Ethics Committee (AUTEC) received the progress report on your ethics application at their meeting on 13 November 2006. The Committee has asked me to thank you for your report.

The request for an extension of one year to 20 December 2007 has been approved.

To enable us to provide you with efficient service, we ask that you use the application number and study title in all written and verbal correspondence with us. Should you have any further enquiries regarding this matter, you are welcome to contact Charles Grinter, Ethics Coordinator, by email at charles.grinter@aut.ac.nz or by telephone on 921 9999 at extension 8860.

On behalf of the Committee and myself, I congratulate you on your research and look forward to reading more about it in future reports.

Yours sincerely

Madeline Banda

Executive Secretary

Auckland University of Technology Ethics Committee

Cc:Simon Pearson simon.pearson@aut.ac.nz