500 m Short Track Speed Skating Start Performance: A Quantification Of Importance And Development Through Dry-Land Means

W. B. Haug

Master of Arts (Kinesiology), University of Connecticut
Bachelor of Arts (History), Brown University

A thesis submitted to Charles Sturt University for the degree of

Doctor of Philosophy

School of Human Movement Studies
Charles Sturt University

Physiology
Australian Institute of Sport

Olympic Winter Institute of Australia

July 2015
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>TABLE OF CONTENTS</td>
<td>ii</td>
</tr>
<tr>
<td>EXECUTIVE SUMMARY</td>
<td>vi</td>
</tr>
<tr>
<td>CHAPTER ABSTRACTS</td>
<td>viii</td>
</tr>
<tr>
<td>PUBLISHED WORKS</td>
<td>xii</td>
</tr>
<tr>
<td>ETHICS</td>
<td>xiii</td>
</tr>
<tr>
<td>CERTIFICATE OF AUTHORSHIP</td>
<td>xiv</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>xv</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>xxi</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xxvi</td>
</tr>
<tr>
<td>CHAPTER ONE</td>
<td>1</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>2</td>
</tr>
<tr>
<td>Statement of the Problem</td>
<td>3</td>
</tr>
<tr>
<td>Research Aims</td>
<td>5</td>
</tr>
<tr>
<td>CHAPTER TWO</td>
<td>7</td>
</tr>
<tr>
<td>REVIEW OF LITERATURE</td>
<td>8</td>
</tr>
<tr>
<td>Introduction</td>
<td>8</td>
</tr>
<tr>
<td>The Relationship between Start Performance and International 500 m Race Outcome</td>
<td>8</td>
</tr>
<tr>
<td>Specificity of Training: Performance Development of an Auxiliary Skill May Benefit a Related Competition Skill</td>
<td>12</td>
</tr>
<tr>
<td>Potential for Dry-Land Sprint Start Training to Enhance 500 m Short Track Speed Skating Start Performance</td>
<td>18</td>
</tr>
<tr>
<td>The Case for the Use of Dry-Land Sprint Starts in the Training of 500 m Short Track Speed Skaters</td>
<td>25</td>
</tr>
</tbody>
</table>
Vertical Power Production and the Start ........................................... 25

Conclusion ......................................................................................... 32

CHAPTER THREE .............................................................................. 34

The Relationship Between Start Performance And Race Outcome In elite 500 m Short Track Speed Skating ........................................... 36

Introduction ......................................................................................... 37

Methods ............................................................................................. 38

Results ................................................................................................. 39

Discussion ......................................................................................... 44

Practical Applications ................................................................. 47

Conclusion ......................................................................................... 47

CHAPTER FOUR ................................................................................. 49

A Lower Body Kinematic Comparison Of The Short Track Speed Skating Start And Dry-Land Sprint Literature .................................. 51

Introduction ......................................................................................... 52

Methods ............................................................................................. 53

Results ................................................................................................. 56

Discussion and Implications ................................................... 63

Conclusion ......................................................................................... 68

CHAPTER FIVE .................................................................................. 69

The Impact Of Dry-Land Sprint Start Training On Short Track Speed Skating Start Performance ................................................ 71

Introduction ......................................................................................... 72

Methods ............................................................................................. 73

Results ................................................................................................. 77
Discussion ............................................................................................................. 80
Practical Applications ............................................................................................ 83
Conclusions ............................................................................................................ 83

CHAPTER SIX ....................................................................................................... 84
Differences In End Range Of Motion Vertical Jump Kinetic And Kinematic Strategies Between Trained Weightlifters And Elite Short Track Speed Skaters ................................................................................. 86
Introduction ........................................................................................................... 87
Methods .................................................................................................................. 89
Results ..................................................................................................................... 93
Discussion .............................................................................................................. 100
Practical Applications ............................................................................................ 104

CHAPTER SEVEN .................................................................................................. 106
Learning The Hang Power Clean: Kinetic, Kinematic, And Technical Changes In Four Weightlifting Naïve Athletes Over Long-Term Training .................................................................................................. 108
Introduction ........................................................................................................... 109
Methods .................................................................................................................. 110
Results ..................................................................................................................... 114
Discussion .............................................................................................................. 126
Practical Applications ............................................................................................ 137

CHAPTER EIGHT .................................................................................................. 138

DISCUSSION .......................................................................................................... 139

CHAPTER NINE .................................................................................................... 150

CONCLUSIONS ..................................................................................................... 151
The short track speed skating (STSS) race start (i.e. from start line to first block of first corner) is potentially overlooked as a training variable in most elite environments. Although the start is indicated to predict 500 m race outcome, the magnitude of relationship is currently unknown. In limited ice time environments, the start is most commonly trained exclusively on-ice. Thus start training competes with other training variables relevant outside of the 500 m event for training resource time. Therefore, the purpose of this thesis was to systematically determine the relationship between the start and international 500 m race outcome and, if warranted, to determine and evaluate alternative off-ice methods of effective start training.

To perform this investigation: tau rank correlations were used to compare skater position entering first corner (i.e. start performance) with race outcome over three years of World Cup competitions and two Olympic Games (Chapter 3). Considering these results, determining the kinematic similarity between the dry-land sprint start and the on-ice start was required as the dry-land sprint start was identified as a potential means to improve on-ice start performance. Previous works performed with long track speed skaters have demonstrated biomechanical similarity between the speed skating and dry-land sprint start; thus, a kinematic comparison of the STSS start and the dry-land sprint start was performed both intra-athlete and with the sprint literature (Chapter 4). The application of these findings warranted an 8 week dry-land sprint start intervention (4 weeks control, 4 weeks intervention) utilizing elite and trained skaters. A crossover design (control followed by intervention) was used to compare changes in on-ice start time pre- to post- over four weeks of 14.43 m dry-land sprint start training (three sets of three starts performed two times per week; Chapter 5). These results informed the investigation to consider alternative gym-based power training, which could potentially benefit on-ice start performance, such as jump and weightlifting training as both have been reported to improve dry-land sprint start performance. To compare the efficacy of both modalities, end range of motion vertical jump kinetics were compared between two groups of power-trained athletes, one trained exclusively in vertical jumping (i.e. short track speed skaters) and the other in vertical jumping and weightlifting (i.e.
weightlifters). Differences in overall and end range of motion kinetics including timing of hip and knee joint deceleration and decrease in vertical velocity between peak and toe off were compared between groups (Chapter 6). These results, then directed an investigation to explore the benefits of weightlifting training on previously jump-trained elite athletes and quantify the time investment necessary to reach power benefit with weightlifting training. This theme was explored with four individual elite athletes naïve to weightlifting training detailing changes in indices of vertical jump performance and movement kinematics over a five-month learning period (Chapter 7).

The results of the thesis are: Start performance during international STSS competition is important as a very large relationship between start performance and race outcome was observed for both elite men and women with the strength of relationship tending to increase with a decrease in absolute race time (Chapter 3). STSS start kinematics demonstrated equivalence to the dry-land sprinting literature with similarities observed in sagittal plane hip and knee joint angles and horizontal velocity over the first few strides (Chapter 4). The STSS start can be effectively improved through a supervised dry-land sprint start intervention in as little four weeks with an expected small, but worthwhile improvement in start performance (Chapter 5). An implication from the cross-sectional comparison of state and national calibre weightlifters and STSS athletes was that long-term weightlifting and jump training may be superior to jump training alone in the development of vertical power. As weightlifters demonstrated superior end range of motion jump kinetics (i.e. less decrease in vertical velocity between peak and toe off, later deceleration of the hip and knee joint) as compared to STSS jump trained athletes (Chapter 6). Weightlifting training produces consistent kinematic changes with learning and may be a useful method of vertical power development as compared to jump training in previously jump trained elite athletes. This is supported by the finding that all four elite athletes achieved improvements in vertical jump performance after only four weeks of training with the hang power clean from a naïve state (Chapter 7).
CHAPTER ABSTRACTS

Abstract Study 1: The Relationship Between Start Performance And Race Outcome In Elite 500 m Short Track Speed Skating

Initial 14 m start performance has substantial influence on 500 m race outcome at the international level yet the relationship has not been systematically quantified. The purpose of this investigation was to examine the relationship between rank position entering first corner (RPEFC) and race outcome and to understand how this relationship changes with competition round and absolute race intensity. Data were compiled from 2011-2014 World Cup seasons and 2010 and 2014 Olympic Winter Games. Association between RPEFC and race outcome was determined through Kendall’s tau rank correlations. A visual comparison was made of how the relationship changes with relative competition level (race tau correlations were sorted by competition round), and with race intensity (race tau correlations were sorted by within-event winning time). A very large relationship between RPEFC and race outcome was observed (correlations for; cohort: $\tau=0.60$, men: $\tau=0.53$ and women: $\tau=0.67$). When examined by competition round (quarter- to A-finals), no substantial change in relationship was observed (men: $\tau=0.57$ to 0.46; and women: $\tau=0.73$ to 0.53). However, when the start performance relationship was considered by within-event winning time, the relationship strength increased with decreasing time (men: $\tau=0.61$ to $\tau=0.46$; women: $\tau=0.76$ to $\tau=0.57$, fastest to 7th and 8th fastest combined respectively). These results establish and quantify RPEFC as an important aspect of elite short track 500 m race outcome. RPEFC as an indicator of race outcome becomes increasingly important with absolute race intensity suggesting that RPEFC capability is a discriminating factor for competitors of similar top speed and speed endurance capabilities.

Abstract Study 2: A Lower Body Kinematic Comparison Of The Short Track Speed Skating Start And Dry-Land Sprint Literature

The relationship between the short track speed skating (STSS) and dry-land sprint start is unknown. Therefore, the purpose of this investigation was to perform a robust kinematic comparison of the elite STSS start and the dry-land sprint
Six elite skaters performed two electronically timed maximal effort STSS starts and 24 hrs earlier, two dry-land sprint starts of 14.43 m with 2D marker trajectories filmed with a 5 camera motion analysis configuration. Due to calibration issues, angular kinematics were compared between STSS and dry-land sprint literature (Murphy, Lockie et al. 2003, Debaere, Delecluse et al. 2013). Maximum and minimum sagittal hip and knee joint extension values over the standing start push-off were hip: 153.7 ± 7.9°; knee: 137.9 ± 7.8°; and hip: 85.1 ± 9.6°; knee: 64.8 ± 7.0°, respectively, with only minimum hip angle disagreeing with a previous dry-land investigation (Debaere, Delecluse et al. 2013). Maximum and minimum hip and knee joint extension values over the first full stride were hip: 148.3 ± 7.8°; knee: 152.1 ± 11.6° and hip: 91.5 ± 11.1°; knee: 61.6 ± 8.7°, respectively, with only maximum hip angle disagreeing with two previous dry-land investigations (Murphy, Lockie et al. 2003, Debaere, Delecluse et al. 2013). On-ice ground contacts tended to be longer (ES=3.14-5.70) and flight times tended to be shorter (ES=2.11-6.87) compared to dry-land over the 14.43 m distance (initial seven contacts and six flights). Sprint times were 2.69 ± 0.23 s and 2.50 ± 0.16 s for on-ice and dry-land, respectively. When these findings are compared to the dry-land sprint start literature, close similarity exists in sagittal hip and knee kinematics, some similarity exists in movement speed, and ground contacts tend to be longer and flight times shorter on-ice compared to dry-land.

Abstract Study 3: The Impact Of Dry-Land Sprint Start Training On Short Track Speed Skating Start Performance

The purpose of this investigation was to determine the effect of a dry-land sprint start intervention on 14.43 m short track speed skating (STSS) start performance in trained and elite skaters. Nine highly trained short track speed skaters participated in this crossover design investigation. All athletes completed an initial control period (approximately three weeks), consisting only of normal STSS training followed by a four week training intervention. The training intervention consisted of two specific sessions per week in which subjects performed nine electronically timed maximal effort 14.43 m linear dry-land sprint starts in addition to all normal STSS training. Overall training was consistent for all athletes between control and intervention
Prior to and after the control and intervention periods, athletes performed three electronically timed dry-land and three on-ice 14.43 m maximal effort sprint starts with each condition separated by 24 hrs. There was no substantial change in 14.43 m on-ice start performance following the control period (Mean Δ: -0.01 s, 95% Confidence Limits (CL): -0.08 to 0.05 s; Effect Size (ES): -0.05; Trivial). However, despite no dry-land sprint start training a small effect was observed for their dry-land start performance (Mean Δ: -0.07 s, 95% CL: -0.13 to -0.02 s; ES: -0.49). The intervention elicited a small improvement both on-ice (Mean Δ: -0.07 s, 95% CL: -0.13 to -0.01 s; ES: -0.33) and dry-land (Mean Δ: -0.04 s, 95% CL: -0.09 to 0.00 s; ES: -0.29) 14.43 m sprint start performance. The reported results indicate the STSS start can be effectively trained through a supervised, dry-land sprint start intervention.

Abstract Study 4: Differences In End Range Of Motion Vertical Jump Kinetic And Kinematic Strategies Between Trained Weightlifters And Elite Short Track Speed Skaters

The purpose of this investigation was to identify differences in end range of motion (ROM) kinetic and kinematic strategies between highly resistance and vertical jump trained athletes and controls. Weightlifters (WL: n=4), short track speed skaters (STSS: n=5) and non-resistance trained controls (C: n=6) performed six standing vertical squat jumps (SJ) and countermovement jumps (CMJ) without external resistance. Jump testing was captured with a 15 camera motion analysis system synchronised with two in-ground force plates. During SJ, there were large effects for the difference in time before toe off of peak vertical velocity between WL to STSS and C (ES: -1.43; ES: -1.73; respectively) and for the decrease between peak and toe off vertical velocity (ES: -1.28; ES: -1.71; respectively). During CMJ, there were large effects for the difference in time before toe off of peak vertical velocity between WL to STSS and C (ES: -1.28; ES: -1.53; respectively) and for decrease between peak and toe off vertical velocity (ES: -1.03; ES: -1.59; respectively). Accompanying these differences for both jump types were large effects for time of joint deceleration prior to toe off for all lower body joints between WL compared to C with large effects between WL and STSS at the hip and between STSS
and C at the ankle. These findings suggest that the end ROM kinetic and kinematic strategy used during jumping is group specific in power-trained athletes, with weightlifters exhibiting superior strategies as compared to resistance and jump trained short track speed skaters.

**Abstract Study 5: Learning The Hang Power Clean: Kinetic, Kinematic, And Technical Changes In Four Weightlifting Naïve Athletes Over Long-Term Training**

The investment in learning required to reach benefit with weightlifting training is currently not well understood in elite athletes. The purpose of this investigation was to quantify changes in vertical jump power production and kinematic variables in hang power clean (HPC) performance during the learning process from a naïve state in a multiple single subject research design. Four elite athletes undertook HPC learning for approximately 20-30 min twice per week over a 169 day period. Learning was supervised by a qualified strength and conditioning professional and taught via a top-down approach (Duba, Kraemer et al. 2009). Changes in parameters of vertical power production during squat jump (SJ) and countermovement jump (CMJ) were monitored from baseline (day 0) and at three additional occasions. HPC movement kinematics and bar path traces were monitored from day 35 and at three additional occasions particular to the individual’s periodised training plan. Descriptive statistics were reported within-athlete as mean ± SD. We observed a 14.1 - 35.7% (SJ) and a -14.4 - 20.5% (CMJ) increase in peak power across the four jump testing occasions with improvements over the first four weeks (SJ: 9.2 - 32.6%; CMJ: -2.91 - 20.79%). Changes in HPC movement kinematics and barbell path traces occurred for each athlete indicating a more rearward directed centre of pressure over the concentric phase, greater double knee bend during the transition phase, decreased maximal plantar flexion, and minimal vertical displacement of body mass with HPC learning. Considering the minimal investment of 4 weeks to achieve increases in vertical power production, the benefits of training with HPC justified the associated time costs for these four elite athletes.
PUBLISHED WORKS


Submitted


ETHICS

The following studies involved human subjects and received ethical approval from human research ethics committees outlined below.

Study 2 – “A kinetic and kinematic comparison of dry-land and short track speed skating start motions”

Ethics approval number 20130214 by the Australian Institute of Sport’s Ethics Committee on 18th February, 2013

Ethics approval number 2013/037 by Human Research Ethics Committee of Charles Sturt University 15th March, 2013

Study 3 – “The effects of a dry-land sprint start intervention on 500 m short track speed skating start performance”

Ethics approval number 20140409 by the Australian Institute of Sport’s Ethics Committee on 14th April, 2014

Ethics approval number 2014055 by Human Research Ethics Committee of Charles Sturt University 8th May, 2014

Study 4 – “Comparisons of vertical jump parameters between elite short track speed skaters and national level Olympic weightlifters”

Ethics approval number 20130214 by the Australian Institute of Sport’s Ethics Committee on 18th February, 2013

Ethics approval number 2013/037 by Human Research Ethics Committee of Charles Sturt University 15th March, 2013

Study 5 – “The effects of long-term hang power clean training on vertical power and technical parameters in naïve elite athletes”

Ethics approval number 20130216 by the Australian Institute of Sport’s Ethics Committee on 18th February, 2013

Ethics approval number 2013/037 by Human Research Ethics Committee of Charles Sturt University 15th March, 2013
CERTIFICATE OF AUTHORSHIP

I hereby declare 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 at Charles Sturt University or any other educational institution, except where due acknowledgment is made in the thesis. Any contribution made to the research by colleagues with whom I have worked at Charles Sturt University or elsewhere during my candidature is fully acknowledged. I agree that this thesis be accessible for the purpose of study and research in accordance with the normal conditions established by the Executive Director, Library Services or nominee, for the care, loan and reproduction of theses.

Name: William Haug

Signature: William Haug

Date: 1/8/15
ACKNOWLEDGEMENTS

When I stepped off the bus in Canberra for the first time in the middle of winter and tried to get into Dale’s driver side door I remember thinking to myself “what did I get myself into”. Little did I know I was about to have one of the best experiences of my life. Thank you to everyone I interacted with over my time here; this truly was an amazing experience I will never forget.

Dr Dale Chapman- For being my first line of support both as a coach and PhD student over this entire process. For grinding it out with me these past few months to produce a project we are all very proud of. For placing the thesis above other work and for foregoing weekends and nights to get this finished right. For being a driving force and largest influence in what has amounted to the best experience in my life. For going out of your way to bring me over here; it has been incredible and I am very sad to leave as I feel we were just starting to find our research groove. I will always miss the arguments where we would yell at each other for 10 minutes just to realize we were saying the same thing.

Dr Eric Drinkwater- For giving me this opportunity. For having enough belief in our work to fight for us, and to find funding from a truly unexpected source. I will always be appreciative of you going that extra mile (kilometer; kilometre) as this wound up being a life changing experience that never would have happened without your persistence. Thank you also for the continued support and level headed consultation during the uncertain times. I am very proud of the work we have put together and how things turned out overall. I will always look back fondly at this experience.

Prof Frank Marino- For making this truly amazing experience possible. For recognizing the potential of our project and for going above and beyond to make it possible. We did not interact much due to my remote location from CSU; however, I understand the level of support you provided and realize the experience would not have been possible in any regard without your support.
Coach Ann Zhang- Grinding it out with you and the boys (and girl) is something I will cherish for as long as I live. I will certainly remember the trips to foreign lands and the excitement of trying to qualify for Olympic Games and that will always bring me joy, but I will remember even more the training days in Melbourne. Riding to the rink early, leaving late, the skating, the dry-land, the gym (of course the gym), the arguments over training, all the planning and execution involved. The experience was special as it was happening, but grows more and more special every day.

Dr Helene Rushby- Helene, I have told you this thirty times, but will mention it once more: there is no way this project would be finished along this timetable without your unwavering support and commitment. Furthermore, you treated my project like it was your own and fought through the bureaucracy to help me accomplish what I needed when I needed. Writing a thesis is tough, but almost impossible when key people are punching a clock. Thank you for being invested in your job and our project. The AIS and all PhD scholars are very fortunate to have you. I will always owe you bigtime.

Geoff Lipshut- For your tremendous support during my tenure with the squad. For giving us the tools to succeed (both as coaches and as researchers) and for your unwavering passion for Australian Olympic Winter Sport. You are a true professional and example of what a CEO should be. I am lucky to have worked under you. Thank you for making this experience absolutely incredible.

Prof Chris Gore- For having me as part of your team. For being a fair and supportive department head; for showing me the right way to lead science professionals and run a department as special and as world renowned as AIS Physiology. I will always consider myself lucky to have worked in AIS Physiology and perhaps even more so to have worked in your department. Thank you for all of your help and support along the way and for helping to make my time at AIS one of the most special in my life.

Prof William Kraemer- For showing me the limits of scientific greatness. I must admit I did not fully appreciate your genius while I learned from you; however, with passing time I gain more and more perspective. By the time I
am done, if I can make a tenth of the contribution you have, it will have been a very successful career. Thank you for allowing me into the Kraemer family, for educating me, and for inspiring me to achieve. I will always view myself as a product of the Kraemer tree.

Coach Gerard Martin- What can I say Coach, you have been like a father to me. For teaching me that there is a right way to do things and to carry yourself; that the process is more important than the outcome. That with faith and consistent effort things will always work out. Sometimes it is hard to place the process over short term rewards, but I always go back to the way you raised us as budding professionals. Thank you for helping to build my scientific and coaching foundation, but more so for making me a better man.

Dr Nick Flyger- First and foremost, for helping a stranger find his way into the AIS. Without your help this document would not even be possible. Second, for always being there for me when I need an experienced ear or shoulder to lean on. Finally, for your integrity; you are the moral model in which I try to base decisions off of. Thank you for everything.

Alex, Andy, Army, Deanna, Nate, Pierre, and Ronald- I love all of you; I mean that. I am sorry that I am not there anymore to watch you improve and compete at the highest level.

Coach Julian Jones- For being just a tremendous resource and mentor during my entire time at AIS. For taking great care of me so I could service athletes maximally and complete our project. And on a more personal note for always finding time to sneak in a call or a chat to help educate me in both strength and conditioning and weightlifting despite being tremendously busy. You went out of your way to help me out even though I did not work directly for you and I just want you to know that I will always be appreciative.

Marilyn Dickson- Maz, you are the best and everyone knows it. You were the soul of Physiology (which was always a great place to work) and I can’t begin to tell you just how many of my days you brightened.
Dr Kyle Pierce- For being a fantastic mentor out of the kindness of your heart. For inviting me to come visit and learn from you despite not knowing me. For always answering my calls and imparting upon me your vast weightlifting knowledge. I will always consider you a mentor and a friend and in the future it is my goal to treat other young professionals the way you have treated me.

Renee Appaneal and Nick Allen- First, for helping our athletes develop both on the ice and as young people. Second, for being good people and colleagues during my time at AIS. You both will always be a big part of the 2014 Olympic campaign; an experience I will never forget as long as I live.

Geoff Henke- For being a fantastic leader and true gentleman. I absolutely loved to hear your stories about past Olympics and professional ice hockey in Australia. Thank you for putting up with me and for allowing me to represent your fine organization.

OWIA Staff- Definitely for putting up with me and my weird habits: the messy desk, the huge tubs of yogurt lying around and the weird American stories. Also, for helping me out professionally; for always giving us the support we needed and for really looking out for our athletes… for being passionate about the athletes and about the institute. Thank you all. I will be sure to say hello to my mother for you.

Dr Wayne Spratford, Dr Elissa Phillips, and Dr John Baker- For all of your support on multiple studies of this thesis. Without your expertise and time invested this project would not have been possible. Thank you very much; I am very appreciative.

Nick, Christine, and Helen of Library Services- For taking a vested interest in our project; for always getting me what I needed in a short amount of time and for always going that extra mile (kilometre). You have a well-deserved reputation for being one of the strongest branches at AIS. Thanks much

Lisa McLean and Nicola Rybarczyk- I have not been lucky enough to interact with either of you much as of late, but I certainly have not forgotten all of the help you provided to me when I first arrived. In fact, I probably
would have needed to delay my arrival a whole semester if it wasn’t for your hard work and genuine care. I will never forget that. Thank you for going above and beyond your job duties and for making feel so welcome.

Dr Lisa Elkington and Dr Liam Byrne- There is really a laundry list of reasons to thank you: For being great friends, for listening to my problems on the daily, for introducing me to coffee, for the hundred dinners you invited me too, for Five Friends, for letting me live with you on multiple occasions, for salmon parties, for talking to me when I was just “the weird American”, for peach bellinis, for listening to my problems, and for being a major reason why Australia has been such a great experience personally. Hopefully I will be back soon.

Kym Williams- For being a good friend pretty much from my first day at AIS. I always enjoyed coming to the gym; not only to lift, but to talk with you about research and just life in general. No matter where I go, I will always consider you a lifelong friend. Also, for your support on Study 4; you really stepped up to make that control group happen in a hurry. That study is now my favourite in the entire thesis.

Dr Nick Brown- For having me as part of your team. For making me feel like an important piece of AIS. Despite your tremendously busy schedule, for finding time to listen to my ideas, and most importantly, for making AIS a tremendously special organization to be part of.

Tim Kelly- For all of your support during my time at AIS. From the day I arrived to my last day, I always felt like you had my best interests in mind and always made me feel like an important piece of AIS. Thank you very much, I will always be appreciative of your support and attitude.

Prof. Rob Robergs- Thank you for stepping in and taking over the project despite a myriad of other professional and personal responsibilities. I found your comments always insightful and educational, your thought process always rational, and your support always present.

Dr Jack Cannon- For stepping in and seeing the project through to completion. Also, for your valuable comments, many of which made the
final product significantly stronger. Thank you very much for your detailed and thorough input.

The AIS S&C Staff- I will always treasure my gym times at the AIS; talking shop and having a good time. Thank you for the times and best of luck to all of you.

Dr Lucy Parrington and Mel Penn- For being my biomechanics support and lifeline in Melbourne. Lucy, I appreciate your advice and help with VICON despite no immediate benefit to yourself and Mel thanks for your help with data collection; bum knee and all.

Dr Robert Curran- Your course was tough; actually very tough. However, it is 7 years later and I still retain the vast majority of your teachings. Thank you very much for being a foundational pillar of my scientific knowledge; I will always be appreciative.

Dr David Martin- For hooking me into the AIS system; without you this experience probably would not have been possible. Also, for your enthusiasm; your attitude every single day is an inspiration to the department.

Cinnamon and LBC- Just for being dudes. For battling it out with me on the daily; those were some of the best times. #Boysclub #Bieber #Yolo

Nick Hunter- For your support and passion for winter sport. Thank you for making our program special. For your advice and willingness to help me and listen to me during my entire time at AIS.

Jerilyn Gusmanos- For your expertise in all products Microsoft. Also, for being the best bosslady ever and a great long-time friend.

Dr Kristie Taylor- For your advice on the overall project and specifically on single subject research design.

Dr Christian Stricker- For taking time out of your schedule to help improve the science of a total stranger. Although our conversations were two years ago, a few of the points still remain with me.
LIST OF FIGURES

Figure 1. Geometry of starting line in relation to first corner entrance. While starting grid is perpendicular to straightaway, actual line of movement during the start is directly towards outside of first block and thus favours inside starting positions. From (Maw, Proctor et al. 2006). .......................... 10

Figure 2. The potential portions of a short track speed skating course where passing generally occurs. From Bullock, Martin et al. (2008). .................................. 12

Figure 3. The effects of angle-specific maximal isometric knee extension training on isometric and 1RM back squat strength. From Zatsiorsky and Raitsin (1974). .................................................................................................................. 18

Figure 4. The sinusoidal motion of speed skating as a function of gliding in conjunction with the horizontal push off. From de Koning and van Ingen Schenau (2000). ........................................................................................................ 21

Figure 5. A birds-eye trace of the left (top) and right (bottom) skate during the sprint start. Note the increasing movement in the frontal plane with each stride. From de Koning et al. (1995). ................................................................. 23

Figure 6. A birds-eye trace of each skate during the 2nd stroke (top) and 8th stroke. From de Koning et al. (1995). ................................................................. 24

Figure 7. A frequency distribution relating rank position entering first corner (RPEFC) with overall 500 m race outcome A) for the entire cohort; B) for men; and C) for women .................................................................................................................. 41

Figure 8. The relationship between rank position entering first corner (RPEFC) and 500 m race outcome with progressive competition round from quarterfinals through A-finals for A) men; and B) women. Trend line represents line of best fit of the data. ................................................................. 42

Figure 9. The relationship between rank position entering first corner (RPEFC) and 500 m race outcome with absolute race intensity for A) men; and B) women. As an indirect measure of absolute race speed, races were ranked from fastest to slowest within each event. Trend line represents line of best fit of the data ........................................................................................................ 43
Figure 10. Average absolute difference in race time between winning A-final and average quarterfinal time for two series of four seasons of international 500 m competition spaced a decade apart for A) men and B) women. Trend lines represent lines of best fit for each data set. .......................... 44

Figure 11. Schematic representation of the data collection set-up (not to scale) with filled triangles representing infra-red light gates, small filled circles representing the calibration spaces utilized and the shaded triangles demonstrating the focal areas for each Photron camera. .......................... 56

Figure 12. The short track speed skating (STSS) standing start. Photos demonstrate: start position, peak extension of the standing start, peak flexion of the standing start, peak extension of the first stride, peak flexion of the first stride; respectively ........................................ 56

Figure 13. Ground contact (A) and flight (B) times (mean ± SD) for the first seven strides of the short track speed skating (STSS) (●) and dry-land sprint starts (■) (n=6). .......................... 62

Figure 14. A comparison of individual on-ice and dry-land 14.43 m sprint start times (s). r=0.93; p<0.001) with the equation for the line of best fit y=0.64x+0.79. Dotted lines are 95% confidence limits. .......................... 62

Figure 15. Total average weekly training volume for Elite and Trained skaters over the control and intervention periods. Training during this time was divided into cycling, dry-land skating imitation, gym-based resistance training, and on-ice. ................................................................. 77

Figure 16. Absolute group mean (n=9) change (solid symbol and horizontal line) with 95% Confidence Limits, and individual mean (n=3) change (open symbol) for Control on-ice (●), Control on dry-land (■), Intervention on-ice (▲), and Intervention on dry-land (♦) for absolute sprint performance. ..... 79

Figure 17. Effect sizes and 95% CLs of pre- to post-intervention difference in 14.43 m on-ice and dry-land sprint time (s) for the control and intervention. The shaded area indicates where effect size is trivial; an effect size of <-0.2 with error bars expanding >0.2 show an unclear result. ....... 79
Figure 18. Data collapsed across investigation periods for the relationship between mean (n=29) dry-land and on-ice 14.43 m sprint time (s) control and pre- (○) with dashed line of best fit post- (■) intervention with solid line of best fit.................................................................80

Figure 19. Between-group effect sizes for peak displacement in cm (●), peak concentric force/ (■), peak concentric power/kg (▲), and peak concentric velocity in (♦) during SJ for A) WL vs ST; B) WL vs C; C) ST vs C; and during CMJ for D) WL vs ST; E) WL vs C; F) ST vs C. Error bars show 95% confidence limits of the actual effect size. The shaded area indicates where effect size is trivial; an effect size of >0.2 with error bars expanding <0.2 show an unclear result...............................................................95

Figure 20. Between group effect sizes for peak velocity time differential to toe off (closed circle), peak velocity differential to toe off (closed square), COM height differential between standing and toe off (closed triangle), start of initial hip deceleration compared to toe off (open diamond), start of initial knee deceleration compared to toe off (open hexagon), start of initial hip deceleration compared to toe off (open triangle) during SJ for A) WL vs ST; B) WL vs C; C) ST vs C; and during CMJ for D) WL vs ST; E) WL vs C; F) ST vs C. Error bars show 95% confidence limits of the actual effect size. The shaded area indicates where effect size is trivial; error bars expanding through -0.2, 0.0 and 0.2 show an unclear result. ..................................................98

Figure 21. Between group differences (mean ± SD) in timing of A) initial deceleration prior to toe off of the lower body joints for SJ and B) peak velocity prior to toe off for both SJ and CMJ; and C) initial deceleration prior to toe off of the lower body joints for CMJ.........................................................99

Figure 22. Between group differences (mean ± SD) in decrease in velocity between peak and toe off for SJ and CMJ.................................................................99

Figure 23. Between group differences (mean ± SD) between height of COM at toe off and standing COM height for SJ and CMJ..................................................100

Figure 24. Changes in SJ kinetic variables with HPC learning over the four testing occasions for Athlete A (circle), B (square), C (triangle), and D
Each data point represents the mean ± SD of four trials for each athlete.

**Figure 25.** Changes in CMJ kinetic variables with HPC learning over the four testing occasions for Athlete A (circle), B (square), C (triangle), and D (diamond). Each data point represents the mean ± SD of four trials for each athlete.

**Figure 26.** Changes in end range of motion CMJ kinetics: difference between peak and toe off velocity (filled shape); timing of peak velocity relative to toe off (open shape) with HPC learning over the four testing occasions for Athlete A (circle), B (square), C (triangle), and D (diamond). Each data point represents the mean ± SD of four trials for each athlete.

**Figure 27.** Changes in kinematic variables and sagittal plane bar path trace over the four testing occasions for Athlete A. Vertical reference line is drawn from right metatarsal-phalangeal joint at start position; deviation from this line in the finish position indicates the athlete has moved forward or backward during the catch phase. Data collection ceased when the bar reached peak vertical displacement following the catch. Values represent mean (SD) of six to nine trials for the individual athlete.

**Figure 28.** Changes in kinematic variables and sagittal plane bar path trace over the four testing occasions for Athlete B. Vertical reference line is drawn from right metatarsal-phalangeal joint at start position; deviation from this line in the finish position indicates the athlete has moved forward or backward during the catch phase. Data collection ceased when the bar reached peak vertical displacement following the catch. Values represent mean (SD) of six to nine trials for the individual athlete.

**Figure 29.** Changes in kinematic variables and sagittal plane bar path trace over the four testing occasions for Athlete C. Vertical reference line is drawn from right metatarsal-phalangeal joint at start position; deviation from this line in the finish position indicates the athlete has moved forward or backward during the catch phase. Data collection ceased when the bar reached peak vertical displacement following the catch. Values represent mean (SD) of six to nine trials for the individual athlete.
**Figure 30.** Changes in kinematic variables and sagittal plane bar path trace over the four testing occasions for Athlete D. Vertical reference line is drawn from right metatarsal-phalangeal joint at start position; deviation from this line in the finish position indicates the athlete has moved forward or backward during the catch phase. Data collection ceased when the bar reached peak vertical displacement following the catch. Values represent mean (SD) of six to nine trials for the individual athlete.

**Figure 31.** Changes in (A) ANKLE PVD and (B) BB HD MAX for each athlete over the four testing occasions for Athlete A (circle), B (square), C (triangle), and D (diamond). Each data point represents the mean ± SD of six to nine trials for each athlete. X axis short tick marks indicate days from baseline of 62, 124 and 163.
LIST OF TABLES

Table 1. Outline of PhD thesis topic ................................................................. 6

Table 2. Relationship (Pearson Correlation r value) between performance in various training exercises (auxiliary skills) and elite pole vaulting (competition skill) results. From Bondarchuk (2007) ........................................... 15

Table 3. A description of mean (SD) hip (n=8 trials) and knee (n=7 trials) joint kinematics between the elite on-ice STSS Start (STSS Start) and the elite long track speed skating start with long track data referenced from de Koning et al. (de Koning, de Groot et al. 1989) on two elite long track speed skaters (n=1 trial). ....................................................................................... 58

Table 4. A description of mean (SD) hip (n=8 trials) and knee (n=7 trials) joint kinematics between the elite on-ice STSS start (STSS Start), and dry-land sprint starts in trained field athletes (n=20 trials) using a two-point start position (Two-Point Fast; Two-Point Slow) Murphy et al. (Murphy, Lockie et al. 2003) or sub-elite sprinters (n=60 trials) using a three-point start position Debaere et al. (Debaere, Delecluse et al. 2013) (Three-Point). ...... 59

Table 5. 95% confidence limits (95% CL) and effects sizes (ES) for the difference in joint kinematics between the elite on-ice STSS start (STSS Start), and dry-land sprint starts in trained field athletes (n=20 trials) using a two-point start position (Two-Point Fast; Two-Point Slow) Murphy et al. (Murphy, Lockie et al. 2003) or sub-elite sprinters (n=60 trials) using a three point start position Debaere et al. (Debaere, Delecluse et al. 2013) (Three-Point). ....................................................................................... 60

Table 6. Differences in contact times (mean ± SD) for first seven full strides of the on-ice and dry-land sprint start in short track speed skating athletes (n=6), with certainty of the estimate shown with a confidence limit (95% CL) and a magnitude of the difference indicated by an effect size (ES). .... 61

Table 7. Differences in flight times (mean ± SD) for first seven full strides of the on-ice and dry-land sprint start in short track speed skating athletes (n=6), with certainty of the estimate shown with a confidence limit (95% CL) and a magnitude of the difference indicated by an effect size (ES). .... 61
Table 8. Athlete characteristics during vertical jump testing. ....................90

Table 9. Standard SJ and CMJ kinetic parameters (mean ± SD) for the Weightlifters (WL, n=4), Short Track Speed Skaters (STSS, n=5) and Control (C, n=6) groups. ..................................................................................................................94

Table 10. Athlete characteristics at baseline prior to beginning the HPC learning process.................................................................112
CHAPTER ONE
INTRODUCTION

Short track speed skating (STSS) normally requires four skaters to race simultaneously around an oval rink 111.11 m in length contained within a standard size Olympic ice hockey rink. STSS has been an Olympic sport since 1988 with Olympic medal distances contested over 500 m, 1000 m, 1500 m, and 5000/3000 m (male/female) relay. As compared with other racing sports such as long track speed skating and the athletics sprints, STSS exhibits marked deviation due to 1) the immediate lack of designated lane assignments after the race start; 2) head-to-head elimination competition format; and 3) the constraints of the race course dictating counter-clockwise turns over a tight radius of approximately 8 m, often times at speeds approaching maximal. Of all STSS events, the 500 m event is considered the sprint distance with a race completion time approximating the 400 m event in athletics. Despite similarities in distance and performance time, the aforementioned peculiarities of STSS dictate a marked difference in pacing strategy as compared to the athletics 400 m event.

An athlete competing in the 500 m STSS event may tend to place a premium on starting fast relative to their immediate competitors. This is because passing is difficult at the international level as athletes are able to achieve and sustain a close to maximal pace for the entire race (ISU 2012) and the competition rules do not permit contact between athletes thus tending to favour the lead skater. These factors may negate small advantages a skater may possess in top speed or speed endurance. The start is the sole opportunity that allows all skaters to claim a leading bunch position with almost equality (Maw, Proctor et al. 2006, Muehlbauer and Schindler 2011); thus a genuine juncture to seize a lead position and retain this position for the duration of the race. Designation as an Olympic sport has likely resulted in improved competitor pools and scientific attention (e.g. improvements in understanding of technique) resulting in progressively fiercer competition over the past 16 years with the world record falling more than 4 and 5 seconds for men and women respectively since 1988 (ISU 2012). In contrast, the 400 m athletics world record has fallen only 0.68 seconds since 1968 (IAAF 2009). Improvements in skating technique, race strategy, and athlete selection have all potentially led to substantial reductions of absolute
500 m race times and because the race is of relatively short duration, any tangible competitive advantage an athlete can possess over the field, e.g. a fast start, will help maximize an athlete’s odds of advancing through international competitions and achieving podium finishes.

While the start is traditionally developed on-ice, transfer of training principles (Zatsiorsky and Raitsin 1974, Bondarchuk 2007, Bondarchuk 2010) dictate that supplemental dry-land training may provide developmental advantages of novel stimuli and greater degrees of training freedom as it pertains to overall training resource allocation. Of the possible known dry-land training means, programming with dry-land sprint starts may be the strongest candidate considering the established general kinematic equivalence and similar fixed-point rearward based force application between movements previously reported in pre-klapskate long track speed skaters (de Koning, de Groot et al. 1989, de Koning, Thomas et al. 1995). Should dry-land start training prove worthwhile, gym-based vertical power training modalities may also be useful performance development tools as vertical power training is known to improve dry-land sprint start performance (Delecluse, Van Coppenolle et al. 1995, Tricoli, Lamas et al. 2005, Cormie, McGuigan et al. 2010, Lockie, Murphy et al. 2012, Chaouachi, Hammami et al. 2014). Thus, it is possible that land-based weightlifting, and resistance and vertical jump training may both be relevant for the development of STSS start performance, although, it is currently unknown if weightlifting offers additional benefits to resistance and jump training alone.

**Statement of the Problem**

For STSS coaches to appropriately allocate training resources across the physiological, technical, and tactical spectrum, the magnitude of impact purported by each race variable must first be understood. Although previous scientific study (Maw, Proctor et al. 2006, Bullock, Martin et al. 2008, Muehlbauer and Schindler 2011) and general consensus among the international STSS community indicate start performance as a relevant factor in determining elite 500 m race outcome, no works have directly investigated the relationship between initial start performance (e.g. first
Considering STSS athletes are required to concurrently train for up to four race distances of distinct physiological profiles, increased focus in one area of training typically comes at the expense of another. Since the relationship between start performance and 500 m race outcome is currently unknown, it is difficult for even experienced coaches to make informed decisions as to appropriate start training resource allocations.

Adding a layer of complexity to the problem are the constraints on available ice time even within elite STSS environments due to the commercial requirements of many venue operators. Since the start is generally trained on-ice, the skill competes for training allocation within this specific, particularly competitive sub-set of resources instead of the entire resource allocation pool. Considering transfer of training principles (Zatsiorsky and Raitsin 1974, Siff and Verkhoshansky 1998, Bondarchuk 2007, Bondarchuk 2010) in combination with potential biomechanical similarities between the STSS start and the dry-land start (de Koning, de Groot et al. 1989, de Koning, Thomas et al. 1995, Ji, Ji et al. 2000), it is likely, although not empirically demonstrated, that dry-land start training will improve on-ice start performance. Should this direct transfer of training exist, it is likely that other modalities known to develop the dry-land sprint start will also enhance on-ice start performance. Of the supplemental modalities known to develop sprint start performance, weightlifting training is a highly established method. While the ability of weightlifting to develop sprint performance is established in absolute terms (Tricoli, Lamas et al. 2005, Chaouachi, Hammami et al. 2014), research establishing weightlifting training as superior to other established means currently does not exist. This lack of training optimization is particularly problematic for elite short track speed skaters as training priorities far exceed athlete resources. Thus, while the weightlifting movements may potentially improve STSS start performance, it is unknown if the performance benefit is worth the potentially large learning investment for a group of athletes whose training needs already exceed training resources.
Research Aims

As identified in Table 1:

1) To quantify the relationship between start performance and race outcome in elite 500 m short track speed skaters. While it appears likely that performance from start to entering first corner is a relevant variable in determining race outcome, this has not been demonstrated systematically nor has a relationship been quantified.

2) To establish dry-land sprint start training as a potentially relevant training tool for the development of STSS 500 m start performance. This will be attempted through the first direct kinematic comparison of STSS starts with the dry-land sprint literature.

3) To systematically investigate whether the STSS 500 m sprint start can be effectively developed through dry-land sprint start training. This will be attempted through a 4 week dry-land sprint start training intervention study.

4) To identify if trained WL or STSS had superior vertical jump kinetic strategies for the purpose of identifying the potential value of WL training for STSS

5) To explore weightlifting as a means to develop vertical power production with potential implications for developing 500 m STSS start performance. This will be attempted through the long-term tracking of vertical jump power production capabilities as well as kinematic changes in response to long-term hang power clean learning performed by elite short track speed skaters naïve to weightlifting.
<table>
<thead>
<tr>
<th>Key research question</th>
<th>Study sequence</th>
<th>Title of study</th>
</tr>
</thead>
<tbody>
<tr>
<td>What is the relationship between the start and race outcome in elite 500 m short track speed skating?</td>
<td>Study 1</td>
<td>The Relationship Between Standing Start And Race Outcome In Elite 500 m Short Track Speed Skating</td>
</tr>
<tr>
<td>Is the dry-land sprint start a relevant training tool for the short track speed skating 500 m start?</td>
<td>Study 2</td>
<td>A Lower Body Kinematic Comparison Of The Short Track Speed Skating Start And Dry-Land Sprint Literature</td>
</tr>
<tr>
<td>What are the effects of a dry-land sprint start intervention on short track speed skating 500 m start performance?</td>
<td>Study 3</td>
<td>The Impact Of Dry-Land Sprint Start Training On The Short Track Speed Skating Start</td>
</tr>
<tr>
<td>Do weightlifting trained athletes demonstrate superior vertical jump kinetics as compared to short track speed skaters?</td>
<td>Study 4</td>
<td>Differences In End Range Of Motion Vertical Jump Strategies Between Trained Weightlifters And Elite Short Track Speed Skaters</td>
</tr>
<tr>
<td>Are the potential benefits of weightlifting on vertical power production worth the learning investment?</td>
<td>Study 5</td>
<td>Learning The Hang Power Clean: Kinetic, Kinematic And Technical Changes In Four Weightlifting Naïve Athletes Over Long-Term Training</td>
</tr>
</tbody>
</table>
CHAPTER TWO
REVIEW OF LITERATURE

Introduction

Considering many elite short track speed skating (STSS) coaches allocate training resources away from the race start due to constraints on available ice time, the ability to train the start in a different environment would free ice time to devote to other skill and physical components vital to performance improvement. While the determination of a transfer of training effect from off-ice to on-ice starting may be novel, it can only be deemed worthwhile should a relationship between start and overall performance exist. Thus, this review intends to first provide supporting evidence for the importance of start performance on elite 500 m race outcome; the race distance strongly implicated to depend on start capability (Maw, Proctor et al. 2006, Muehlbauer and Schindler 2011). Once the relationship between the start and overall performance has been established, this review intends to then build a theoretical construct for the use of dry-land sprint start training in the development of on-ice sprint start performance; first, by demonstrating the potential for a transfer of training effect between two similar movements, then by establishing the robust kinematic similarities between motions. This review then intends to cover the potential efficacy of another off-ice training means indicated to develop sprint start performance, weightlifting, with the potential benefits and drawbacks of this established modality on 500 m performance discussed. In totality, this review should provide evidence that start performance is crucial in determining elite 500 m STSS race outcome and that training the start off-ice should be considered as an alternative or supplemental means of enhancing start performance with multiple options worthy of consideration.

The Relationship between Start Performance and International 500 m Race Outcome

Scientific investigation has supported the long held belief of the international STSS community that there is a positive relationship between start time performance and race outcome at the 500 m distance. This relationship was first identified by Maw et al. (2006) and then confirmed by Bullock et al. (2008) who analysed a season of International Skating Union
World Cup events and World Championships and determined that in men’s events 71% of winners led the race after the initial half lap with no winners coming from outside of second place at the half-lap time point. Maw et al. (2006) and later Muehlbauer and Schindler (2011) determined significant Kendall’s tau rank correlations between starting grid position and 500 m race outcome. These results suggest that start performance is of such importance that being slightly closer to the first block due to the geometry of the start line in relation to the entrance to first corner provides a statistical advantage at the international level for both men and women (Figure 1).

Interestingly, the strength of this relationship has been shown to decrease with race distance (Muehlbauer and Schindler 2011) and to increase by competition round with the semi-finals/finals showing stronger relationships than heats/quarter-finals (Maw, Proctor et al. 2006). Maw (2006) attributes this change in relationship to discrepancies in the talent pool at different stages of an event. Being that standard international competition is elimination format; higher ranked skaters are better able to overcome a disadvantageous or poor start in earlier rounds versus weaker competition than during the semi-finals and finals versus primarily other top skaters.

Thus, while the start is of importance throughout an international 500 m competition, this importance appears to increase with round and thus equivalence in overall ability between competitors.

While the works of Maw et al. (2006), Muehlbauer and Schindler (2011), and Bullock et al. (2008) put forth and strongly support the concept of start performance as a relevant factor in elite 500 m STSS race outcome, further inquiry into the relationship is still required as all three (3) works taken together represent the total body of literature on the topic and as a synthesized work still fail to fully quantify the relationship. The primary research need is a robust investigation directly analysing the correlation between start performance and race outcome in elite 500 m STSS competition. While the works of Maw et al. (2006) and Muehlbauer and Schindler (2011) both indirectly implicate start performance as a relevant factor in 500 m race outcome, neither study directly investigated start performance with both studies analysing only the relationship between starting grid position and race outcome. While Bullock et al. (2008) directly compared a measure of elite start performance with race outcome, they
quantified start performance as the first half-lap split time. This measure is perhaps not the purest indicator of starting performance as it factors the skill of skating the first corner as well as half of the first straight, both of which are dominated by techniques differing from the dry-land sprint technique characteristic of initial race acceleration. Additionally, Bullock et al. (2008) utilized a limited data set, only analysing 6 total competitions worth of 500 m races. When factored in conjunction with choice of start performance demarcation, it is possible the complete relationship between start performance and race outcome is masked by skewed data and extraneous skating skills.

Figure 1. Geometry of starting line in relation to first corner entrance. While starting grid is perpendicular to straightaway, actual line of movement during the start is directly towards outside of first block and thus favours inside starting positions. From (Maw, Proctor et al. 2006).

From the few published works quantifying the importance of start performance on international 500 m race outcome (Ji, Ji et al. 2000, Lee, Back et al. 2006, Maw, Proctor et al. 2006, Bullock, Martin et al. 2008, Muehlbauer and Schindler 2011), all attribute the significance to the limited number of passing opportunities over the course of a race; i.e. passing during elite 500 m competition is difficult. This is most likely due to a multitude of factors. First, the 500 m race is the shortest international
distance at only 4.5 laps, thus there is less time to execute a pass when considered versus longer race distances. Second, because of the short distance, each competitor is capable of skating at maximal, or near maximal speed the entire race so there is less opportunity to use a pacing or tactical strategy to take advantage of competitors moving at substantially sub-maximal speeds. Third, the achieved momentum associated with maximal pace makes safe and legal passing manoeuvres difficult to execute. Finally, and unique to STSS, are the constraints of the course in conjunction with the previously mentioned rationales. While the STSS course allows physical space to accommodate several skaters in parallel, during actual 500 m competition there exists a very limited number of efficient routes or “tracks” an athlete can skate that maximizes speed and minimizes the overall distance travelled. Over the apex of the corner, this number effectively drops off to one track immediately adjacent to the blocks. Due to the inefficiency of all other tracks, passing generally does not occur over the apex of the corner (Bullock, Martin et al. 2008), further reducing the already limited number of passing opportunities and perhaps more importantly, dictating that a pass must occur in its entirety in between corners. Thus, it is not merely enough to achieve a speed greater than a competitor skating at or close to a maximal pace, but the difference in speed must be such that it allows the entirety of the body to pass within an approximately 3 s or 40 m window (Figure 2). The creation of these finite passing windows also provides an advantage to the lead skater who only needs to prepare defensive positions during these finite windows instead of over the length of the entire track.

These finite passing windows (Figure 2) explain the findings of Maw et al. (2006), who suggests the start performance becomes increasingly important with each successive competition round (e.g. quarter- vs semi-finals). Being that STSS is a head-to-head elimination format, each round the comparatively weaker skaters are eliminated, and therefore, with each round it becomes increasingly likely competitors will have similar top speeds and similar abilities to hold speeds close to maximal for the entire race. Thus, for a given competitor it becomes increasingly more challenging to create a discrepancy in speed great enough to move from an in-series position behind to completely in front of an opponent during a passing window. This
is in contrast to the start where all athletes are located in parallel, yet still have a similar ~3 s window to establish a lead position. Additionally, the rules of STSS are set up to protect the lead skater. Since no skater is deemed leading at the start, it is possible to jockey for position with greater assertiveness during the start with a reduced risk of disqualification.

While the importance of start performance in race and overall event outcome has been previously demonstrated in international 500 m STSS competition, the start should be considered a relevant variable in the training of most levels of skaters. While the need to train the start is evident, the optimal training method is currently less clear, especially when the limited availability of ice time is considered as a factor.

![Figure 2](image_url)

**Figure 2.** The potential portions of a short track speed skating course where passing generally occurs. From Bullock, Martin et al. (2008).

**Specificity of Training: Performance Development of an Auxiliary Skill May Benefit a Related Competition Skill**

There is a small amount of published scientific literature identifying the STSS start as important to race outcome and as such a relevant area of training focus. However, to date no published works have sought to compare or examine the effects of different training modalities on start performance. It is likely that maximally developing the start will require at least some repetition of the direct skill on-ice. Considering the constraints on-ice time experienced in even elite training environments, it may be of benefit to supplement on-ice start training with an effective non-ice training modality. In order to advocate the training of the start off-ice, evidence must first be presented demonstrating a transfer of performance from one skill to a related, but distinct second skill.
Both anecdotal and scientific evidence indicates that training adaptations are specific to the imposed demands placed on the system (Sale 1988, Fleck and Kraemer 2004, Zatsiorsky and Kraemer 2006, Bondarchuk 2007). For this reason the direct competition movement performed at competition velocity and intensity is a staple of all conventional training programs. While development of the main sporting movement is an important component for maximization of performance, it may not be the only relevant component, as the movement may additionally be performed in similar, but non-identical conditions, or affected by less similar movements capable of developing a specific capacity, often referred to as transfer of training. This potential benefit of deviation arises from both the general recommendation for variety of training stimuli to prevent any particular stimulus from becoming stale (Garhammer and Takano 2003, Fleck and Kraemer 2004, Baechle and Earle 2008) and the potentially unique neurological benefits of training a given movement under slightly different conditions and force-velocity profiles (Newton, Kraemer et al. 1999, Fleck and Kraemer 2004, Bondarchuk 2007, Bondarchuk 2010). While a variety of different exercises and training modalities have the potential to positively impact the performance of a given competition skill, the level of benefit or transfer from a given skill to a competition skill can vary greatly and is primarily dictated by the overall similarity. Overall similarity between skills may be multifactorial and dependent on the following areas of congruence: A) similarities in overall motor pattern and application of force; B) force-velocity parameters; C) joint angles utilized; and D) relevant performance determining capacities (e.g. the capacity to produce maximal force). Scientific theory as well as best evidence points to a relationship between level of overall transfer and strength of relationship between each individual area of potential congruence. Thus, as it pertains to 500 m STSS, development of the start through alternative means may be effective provided the means demonstrate equivalence with the competition start across areas of congruence.

**Similarities in overall motor pattern and force application.** Equivalence in the joints utilized and sequencing of muscular coordination are central parameters underlying specificity of training and demonstrated to affect transfer of training between sporting movements (Rasch and Morehouse 1957, Thorstensson, Karlsson et al. 1976, Sale 1988, Zatsiorsky and
Providing strong support is the classic investigation by Thortensson et al. (1976) who reported that back squat training benefitted back squat performance to the greatest extent, isometric leg press to a lesser extent, and provided no significant benefit to isometric leg extension. Building upon this work Bondarchuk (2007) used correlational analyses with elite athletes to provide insight into the relationship between competition motor skill and auxiliary motor skills utilized during training. Bondarchuk (2007) demonstrated performance in a training skill co-varies with performance in a competition skill as a function of biomechanical equivalence. Furthermore, and perhaps more importantly, the development of performance in skills most closely resembling the competition motor pattern has the greatest benefit to performance of the competition motor pattern (Bondarchuk 2007, Bondarchuk 2010, Bondarchuk 2011). As shown in Table 2, an athlete’s ability to run at top speed over 30 m is more indicative of elite pole vault performance than is bench press performance. As proposed by Bondarchuk (2007), the underlying cause for the discrepancy in relationship is that the 30 m run is a direct component of the pole vault motor skill whereas the bench press only utilizes some overlapping musculature within a potentially similar, but non-equivalent movement pattern. When developing the 500 m start, if other areas of congruence are held equal, an alternative training means may be effective in developing the competition start as long as both movements exhibit equivalence in employed motor pattern and application of force.
Table 2. Relationship (Pearson Correlation r value) between performance in various training exercises (auxiliary skills) and elite pole vaulting (competition skill) results. From Bondarchuk (2007).

<table>
<thead>
<tr>
<th>Exercise</th>
<th>5.50-5.580m Pole Vault Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>30m run with a flying start</td>
<td>0.865</td>
</tr>
<tr>
<td>30m run from the blocks</td>
<td>0.742</td>
</tr>
<tr>
<td>60m run from the blocks</td>
<td>0.786</td>
</tr>
<tr>
<td>100m run from the blocks</td>
<td>0.705</td>
</tr>
<tr>
<td>Vertical jump</td>
<td>0.660</td>
</tr>
<tr>
<td>Long Jump from Place</td>
<td>0.556</td>
</tr>
<tr>
<td>Triple jump from place</td>
<td>0.624</td>
</tr>
<tr>
<td>5-fold jump from place</td>
<td>0.580</td>
</tr>
<tr>
<td>Pole vault with short run up</td>
<td>0.845</td>
</tr>
<tr>
<td>Long jump with run-up</td>
<td>0.654</td>
</tr>
<tr>
<td>Barbell snatch</td>
<td>0.386</td>
</tr>
<tr>
<td>Half squat with a barbell</td>
<td>0.456</td>
</tr>
<tr>
<td>Bench press</td>
<td>-0.306</td>
</tr>
<tr>
<td>Throwing the shot forward</td>
<td>0.189</td>
</tr>
<tr>
<td>Throwing the shot backward</td>
<td>-0.214</td>
</tr>
</tbody>
</table>

**Force-velocity parameters.** The force-velocity relationship dictates that for a given concentric movement pattern, as the velocity of movement increases, the ability to produce further force decreases (Hill 1938, Cormie, McGuigan et al. 2011). The transfer of training effect from an auxiliary movement to a competition sporting movement is heavily influenced by similarities in the force-velocity relationship of the involved movements (Bondarchuk 2007), also coined velocity specificity (Behm and Sale 1993). Thus, even if motor pattern and application of force is precisely maintained, the level of training transfer may still be affected if the training movement is performed in conditions of much greater or much less resistance than the sporting.
movement (Caiozzo, Perrine et al. 1981, Kamehisa and Miyashita 1983, Häkkinen and Komi 1986, Bondarchuk 2007, Cormie, McCaulley et al. 2007). This effect may be further limited if the neurological intent to perform the auxiliary movement is at a slower speed as compared to the sporting movement (Behm and Sale 1993, Cormie, McGuigan et al. 2011).

Level of equivalence between movements in force-velocity parameters heavily influences the transfer of training effect with numerous studies (Moffroid and Whipple 1970, Lesmes, Costill et al. 1978, Aagaard, Simonsen et al. 1996) identifying larger gains in strength at the velocity of training compared to different velocities. However, intentionally altering the relationship in the training exercise to similar, but distinct profiles may further enhance competition movement performance (Jones, Bishop et al. 2001, Fleck and Kraemer 2004, Cormie, McGuigan et al. 2011). This has been demonstrated through benefits of weightlifting and back squat training on vertical jump performance (Vorobyev 1978, Cormie, McGuigan et al. 2011). While a strong transfer of training effect has been documented between these movements of similar motor pattern and application of force, but different force-velocity profiles, it is paramount to mention the difference in profile between exercises, while significant, still tends to be within a range that still fosters a transfer of training. This is illustrated by the range in peak velocity reported for back squat ($\leq 1.33 \text{ m} \cdot \text{s}^{-1}$) (Stevenson, Warpeha et al. 2010), competition clean and snatch ($1.28-2.06 \text{ m} \cdot \text{s}^{-1}$) (Roman and Shakirzyanov 1978, Roman and Treskov 1983, Harbili 2012), and unloaded vertical countermovement jump ($2.86-3.18 \text{ m} \cdot \text{s}^{-1}$) (McBride, Triplett-Mcbride et al. 1999) performed by trained athletes. These findings imply that while training under different load-velocity relationships may benefit performance, the relationship may be influenced and in some cases dependent on limited deviation from the competition load-velocity profile.

*Joint angles utilized.* There is potential for the range of motion through which joints function to be a relevant factor in determining the magnitude of transfer of training effect between two movements. In strong support of this contention is a study by Zatsiorsky and Raitsin (1974) (Figure 3) in which half the study participants trained isometric leg extension at 70° knee extension and the other half at 130° (180° is convention for maximal
While the 130° group experienced greater increases in isometric strength at the trained angle than did the 70° group, they experienced fewer gains at other angles and gained less strength in 1RM back squat. In addition to this investigation by Zatsiorsky and Raitsin (1974), several other works (Gardner 1963, Lindh 1979, Sale 1988, Fleck and Kraemer 2004, Zatsiorsky and Kraemer 2006) support the notion of joint angle specificity as a relevant factor in the transfer of training effect between movements.

While the mechanisms underlying the relationship between transfer of training and joint angle specificity are currently not well understood, it can be potentially attributed to differences in muscle contractile mechanics at different areas of the length-tension curve (Gordon, Huxley et al. 1966, Edman 2003) or to neurological factors resulting from training differences in central drive specific to the trained range of motion (Aagaard 2003, Sale 2003). Regardless, reviewed areas of congruence held equal, alternative training means may benefit on-ice 500 m STSS start performance should this means demonstrate equivalence in the employed ranges of motion of the relevant joints.

**Relevant performance determining capacities.** While specificity related to movement pattern and force application are important in determining transfer of training effect, evidence exists that the ability of a training exercise to develop a specific relevant capacity is also important, and in some instances may supersede similarities in movement pattern. For instance, the capacity to produce maximal force is known to be important in sprint performance (Delecluse, Van Coppenolle et al. 1995, Baker and Nance 1999, Seitz, Reyes et al. 2014). Although single leg squatting (e.g. Bulgarian split squat) is potentially a closer movement pattern to sprint than is the bilateral back squat, the back squat may produce larger performance gains in sprint performance, potentially due to a greater effect on force production capacity as compared to single leg squatting.
In summary, while maximization of performance in the 500 m STSS start likely requires some direct skill practice, there is evidence to support the hypothesis (as this is yet undetermined) that practicing the STSS start may be complimented by alternative means. The alternative means utilised to complement the direct skill practice should demonstrate close equivalence in overall motor pattern, application of force, force-velocity parameters, and joint angles utilized. This review will now critically discuss the use of specific alternative training modalities as a means to develop the competition start in STSS. The specific modalities of dry-land sprinting and weightlifting have been chosen due to their close equivalence in areas of potential congruence and because they are off-ice, potentially allowing the STSS competition start to be developed independent of what is considered to be limited on-ice training time and resources.

Potential for Dry-Land Sprint Start Training to Enhance 500 m Short Track Speed Skating Start Performance

The motor pattern characteristic of dry-land sprinting (Lockie, Murphy et al. 2012, Debaere, Delecule et al. 2013) and the gliding motion that dominates STSS demonstrate marked kinetic and kinematic differences (van Ingen...
Schenau, de Groot et al. 1983, van Ingen Schenau, de Boer et al. 1987, de Koning, de Groot et al. 1989, de Koning, Thomas et al. 1995); however, the first several steps of both motions share equivalence with the literature describing the long-track speed skating start as comparable to a running sprint start (Djatschkow 1977, de Koning, de Groot et al. 1989, van Ingen Schenau, de Koning et al. 1994, de Koning, Thomas et al. 1995). The overall contribution of individual muscles as well as specific reflex contribution remains to be quantified during the speed skating start and compared to the dryland start; nonetheless, strong evidence of biomechanical equivalence between movements exists. While previous works report sufficient equivalence to suggest a transfer of training between dry-land sprint training and competition start performance, these works are specific to long track, which may produce different kinematics as compared to STSS due to differences in equipment (i.e. blade position on the boot, blade rockering, and blade bend), athlete genetics, and rules of the sport (ISU 2012). While an on-ice sprinting motion may seem counterintuitive considering the biomechanical deviation from the traditional gliding motion, upon further review of physical and physiological factors, it is actually quite intuitive. Human beings are adapted to live on dry-land and our preferred means of rapid self-propelled overland locomotion is the sprint with evidence suggesting inherent possession of a sprint motor pattern (Brown 1911, Grillner 1986, Burke, Degtyarenko et al. 2001, Dietz 2003, Zehr 2005, Zehr, Balter et al. 2007). All else equal, humans achieve the greatest unassisted horizontal accelerations and velocities through sprinting (van Ingen Schenau, de Koning et al. 1994, Delecluse 1997, Krzysztof and Mero 2013, Pavei, Cazzola et al. 2014) thus, it is logical the neuromuscular system solves other fixed-point force application locomotor challenges through a sprinting-based motion.

Shifting from the sprint style start to the traditional gliding motion in skating is necessary due to the peculiarities of surface friction coefficients, further efficiencies in locomotion, and the function of the speed skating blades (van Ingen Schenau and Bakker 1980, van Ingen Schenau, de Groot et al. 1983, de Boer, Schermerhorn et al. 1986, De Koning and van Ingen Schenau 2000). On dry-land, the majority of animal locomotion patterns including bipedal sprinting utilize Newton’s Third Law in its simplest form: for every
action there is an equal and opposite reaction (Ohanion 1985). Thus, to propel oneself forward force is applied at a fixed point in the rearward direction with top speed limited by the ability to create a difference in horizontal velocity between the hip and the contact foot greater than the velocity of the centre of mass (van Ingen Schenau, de Boer et al. 1987, de Koning, de Groot et al. 1989, de Koning, Thomas et al. 1995). While a fixed point force application strategy is possible on-ice, it is ineffective once a modest velocity approaching 7 m•s\(^{-1}\) has been reached (Djatschkow 1977, de Koning, de Groot et al. 1989, de Koning, Thomas et al. 1995). This is because the low coefficient of friction between ice and blade allows an athlete to produce a contributing force while simultaneously gliding forward. It is this ability to apply force to a changing point of application that allows speed skaters to reach speeds in excess of 15 m•s\(^{-1}\) (van Ingen Schenau, de Koning et al. 1994). Since it is impossible to produce force in the rearward direction while gliding forward, an effective push-off is only possible at right angles relative to the gliding direction of the skate. It is this perpendicular force application in conjunction with the glide that creates the sinusoidal motion associated with high velocity speed skating (Figure 4) (van Ingen Schenau, de Boer et al. 1987, de Boer and Nilsen 1989, de Koning, de Groot et al. 1989, de Koning and Van Ingen Schenau 2000).

Considering the interaction between ice and skate blade deem the gliding technique superior only at speeds approaching 7 m•s\(^{-1}\) and above, it is logical the first several strides default to a motion kinetically and kinematically equivalent to a dry-land sprint start. This conclusion is supported by multiple scientific works (de Koning, de Groot et al. 1989, de Koning, Thomas et al. 1995) and is elaborated on below as it pertains to the following biomechanical variables: A) overall movement pattern; B) application of force; C) planes of movement; D) joint angles employed; and E) velocity of movement.
Figure 4. The sinusoidal motion of speed skating as a function of gliding in conjunction with the horizontal push off. From de Koning and van Ingen Schenau (2000).

Overall movement pattern. The dry-land and speed skating start have been described to share a similar kinetic movement pattern characterized by phases of ground contact and flight (de Koning, de Groot et al. 1989, de Koning, Thomas et al. 1995). The general trajectories of the lower limbs also share commonality with phases of acceleration and deceleration in the sagittal plane. Similar to the dry-land sprint start, the speed skating start utilizes plantarflexion during ground contact, which is omitted as much as possible during the on-ice gliding motion to prevent the toe section of the blade from digging into the ice thus causing additional frictional resistance (van Ingen Schenau, de Boer et al. 1987, de Koning, de Groot et al. 1989, de Koning, de Groot et al. 1992). While the literature has determined similarity between dry-land and on-ice sprint start kinematics such as general limb trajectories and the existence of flight and ground contact phases, no direct intra-athlete kinetic or kinematic comparison between mediums currently exist. Therefore, while the relationship between dry-land and on-ice sprint start kinematics has been compared in general terms, a need still exists for the specific quantification.
Application of force. Several works (Djatschkow 1977, de Koning, de Groot et al. 1989, de Koning, Thomas et al. 1995) have documented the first few strides of the long track speed skating start exhibit a fixed point application of force identical to the dry-land sprint start. By the 4th stroke a minor gliding component is evident with the stroke transitioning mostly to gliding by the 8th stroke (de Koning, de Groot et al. 1989). Despite this transition, the 8th stroke has been shown to still display some aspects of a fixed point application of force with plantarflexion still apparent during the push off (de Koning, Thomas et al. 1995). As a generalisation, similarities between dry-land and on-ice sprint start biomechanics have been documented; however, previous works have exclusively utilized pre-klapskate long track speed skaters and have failed to report on specific kinematic variables (e.g. length of skate displacement with each transition step), thus leaving a significant gap in the literature.

Planes of movement. Represented in Figures 5 and 6 are pictorial forms of the pre-klapskate long track speed skating start as performed by elite skaters, indicating less lower body movement in the frontal plane than during the gliding technique, which incorporates a progressive increase in frontal plane leg abduction with each step from rest (de Koning, de Groot et al. 1989, de Koning, Thomas et al. 1995). Although extension of the hip is directed through the sagittal plane to a much greater extent than during gliding, the speed skating start still demonstrates greater movement in the frontal plane than does dry-land sprinting (de Koning, Thomas et al. 1995, Debaere, Delecluse et al. 2013). While scientific investigation into the underlying causes of variation has not yet been addressed, it seems intuitive that some hip abduction in combination with external rotation allows the skate blade to contact the ice at an angle closer to perpendicular thereby maximizing the coefficient of friction. While these previous works have reported similarity between speed skating start and dry-land sprinting start planes of movement, a systematic quantification between surfaces currently does not exist. Furthermore, despite similarity between disciplines, none of the previous works have directly investigated short track speed skaters.

Velocity of movement. While both maximal dry-land sprinting and on-ice speed skating starts involve similar, relatively large horizontal accelerations
from rest, the dry-land sprint start acceleration has been reported to be
greater when comparing studies conducted with high-level athletes.
Debaere et al. (2013) reported horizontal velocities of \(4.28 \pm 0.27 \text{ m/s}^1\) after
the first ground contact and \(5.19 \pm 0.30 \text{ m/s}^1\) after the second contact in
sub-elite male 100 m sprinters. In contrast, de Koning et al. (1989) reported
that these values are not reached for elite male 500 m long track speed
skaters until approximately the 4\(^{th}\) and 6\(^{th}\) contact respectively. Considering
differences in equipment between long track and STSS [i.e. blade position,
rocker (longitudinal blade bend), and curvature (lateral blade bend)] and
potential athlete genetics, similarities in velocity of movement between
STSS and dry-land sprinting are currently unknown.

**Joint angles employed.** From elite inter-athlete analyses, lower body joint
angle sagittal ROMs utilised in the long track speed skating start and
athletics 100 m sprint start (block phase excluded) have been reported to be
near equivalent at the hip (90° to 170° versus 95° to 181°), knee (100° to
160° versus 111° to 165°), and ankle (80° to 140° versus 70° to 133°) during
the contact phase of the second stride respectively (de Koning, de Groot et
al. 1989, Debaere, Delecluse et al. 2013). A 2-point standing start kinematic
analysis utilising recreationally trained field athletes provided further
supporting evidence reporting peak hip and knee extension angles of 141.1°
and 147.8° respectively over the first stride (Murphy, Lockie et al. 2003),
which is comparable to 150° and 160° reported in elite speed skaters (de
Koning, de Groot et al. 1989). While these similarities support the use of
dry-land sprint start training means in the development of the competition
speed skating start, further scientific inquiry is still required as previous
investigations have reported exclusively on long track speed skaters.

![Figure 5](image_url)

**Figure 5.** A birds-eye trace of the left (top) and right (bottom) skate during the sprint start.
Note the increasing movement in the frontal plane with each stride. From de Koning et al. (1995).
Figure 6. A birds-eye trace of each skate during the 2nd stroke (top) and 8th stroke. From de Koning et al. (1995).

Apparent to the naked eye and supported by the body of literature (de Koning, de Groot et al. 1989, de Koning, Thomas et al. 1995), the first several strides of the speed skating start and the dry-land sprint start share great equivalence. This is because up until a speed of 7 m•s⁻¹, sprinting on-ice may be more effective than the traditional gliding motion. Considering it is likely both dry-land and on-ice sprint starts share the same root motor program, it is not surprising significant kinetic and kinematic overlap has been documented (de Koning, de Groot et al. 1989, de Koning, Thomas et al. 1995) in all potential areas of congruence. While previous findings (de Koning, de Groot et al. 1989, de Koning, Thomas et al. 1995, Bondarchuk 2007, Bondarchuk 2010) suggest a transfer of training effect between dry-land sprinting and STSS start performance, further STSS specific research is required as all previous works exclusively reported on pre-klapskate long track speed skaters. While these works are broadly applicable, differences between disciplines may exist as the STSS skate set up differs from the long
track set up (i.e. greater blade offset and blade curvature) potentially creating differences in both start kinetics and kinematics.

The Case for the Use of Dry-Land Sprint Starts in the Training of 500 m Short Track Speed Skaters

The body of scientific evidence suggests the training of the 500 m STSS start on dry-land is a worthwhile endeavour. This is for four main reasons: 1) the start is a relevant factor in determining overall 500 m performance outcome; 2) dry-land and on-ice starts demonstrate great biomechanical similarity; 3) the development of one motor pattern has been demonstrated to affect closely related motor patterns; and 4) The costs associated with ice time have limited the development of the on-ice sprint start in many training environments. As previously discussed, the 500 m sprint start is an important performance variable. However, it is currently overlooked during training due to the higher prioritization of other skills and that the sprint start may potentially be developed through dry-land means, the potential to further explore and quantify the development of on-ice 500 m sprint start through the use of dry-land sprint start training is worthwhile.

Vertical Power Production and the Start

Dry-land sprint start performance has been reported to co-vary with vertical power production (Baker and Nance 1999, Haff 2001, Tricoli, Lamas et al. 2005, Hori, Newton et al. 2008, Requena, Garcia et al. 2011). This is intuitive considering similarities in joint angles (Roman and Shakirzyanov 1978, Garhammer and Gregor 1992, Slawinski, Bonnefoy et al. 2010), regimes of muscular work (Vorobyev 1978, Mero, Komi et al. 1992, Bezodis, Salo et al. 2014), and kinematic sequencing of the lower body musculature (Bobbert and van Ingen Schenau 1988, Garhammer and Gregor 1992, Bezodis, Salo et al. 2014) between movements. Vertical power production is usually quantified through kinetic and kinematic parameters derived during performance of either vertical jump or weightlifting performance. However there is evidence to suggest that between movement differences in power production may have an impact on the training associated adaptations specific to the STSS start.
Support for a relationship between start performance and vertical power production has been reported through both correlational analysis and training intervention. Baker and Nance (1999) reported that the relationship was between $r=-0.51$ and $r=-0.61$ for measures of relative countermovement jump power and 10 m sprint time in professional rugby league players, while Requena et al. (2011) reported an $r=-0.47$ between countermovement jump and 20 m sprint time in well trained sprinters. Importantly, in a training intervention conducted by Delecluse et al. (1995), significant improvements in 10 m sprint time were reported following 9 weeks of high velocity vertical resistance training in well trained sprinters. These findings are supported by Cormie et al. (2010) who determined 2.2% and 3.6% improvements in 40 m sprint time after 10 weeks of power training in relatively weak and strong recreationally trained athletes respectively and by Lockie et al. (2012) who reported increases in 10 m horizontal velocity in recreationally trained field athletes after 6 weeks of either plyometric or moderate to higher velocity resistance training. The ability of power training to influence sprint acceleration has also been demonstrated recently in children with Chaouachi et al. (2014) reporting moderate to large effects of plyometric, resistance, and weightlifting training on 5 m sprint acceleration following a 12 week intervention in 10-12 year old children. In accordance with transfer of training principles, it is likely that the relationship between vertical power production and dry-land sprint start performance also extends to the STSS start.

Despite strong support for the dependence of start performance on vertical power production and the intuitive connection, some training studies have nonetheless failed to find significant benefits of vertical power training on sprint start performance. While McBride et al. (2002) reported improvements in 5 m, 10 m, and 20 m sprint time with 8 weeks of weighted countermovement jump training with a load equal to 30% 1 RM back squat, the level of improvement failed to show significance. Similarly, Tricoli et al. (2005) found insignificant increases in 10 m and 30 m maximum horizontal velocity with 8 weeks of vertical jump and plyometric training. Considering the body of supporting evidence in conjunction with the small n sizes of 9 and 12 for McBride (2002) and Tricoli (2005), respectively, it is
possible the vertical jump interventions did benefit sprint start performance; however, the statistical tools utilized failed to detect the changes.

*Weightlifting to Benefit Vertical Power Production.* Considering the current weightlifting movements have been contested in the Olympics since the 1920 games (Takano 1987), the anecdotal connection between weightlifting performance and vertical power production has been observed and validated by coaches, athletes, and enthusiasts for almost a century. The coaching literature has long supported a robust relationship between weightlifting results and vertical power production (Vorobyev 1978, Takano 1987, Garhammer 1989, Chiu and Schilling 2005, Stone, Pierce et al. 2006, Waller and Gattone 2007, Cormie, McGuigan et al. 2011). Lending further support for such benefits is the large number of athletes from other sports that cross-train with variations of the weightlifting movements (Chiu and Schilling 2005, Cormie, McGuigan et al. 2011). Although not yet scientifically established, training with the weightlifting movements is considered the preferred method to develop vertical power production within the strength and conditioning environment (Ebben and Blackard 2001, Ebben, Carroll et al. 2004, Simenz, Dugan et al. 2005).

Weightlifting training has been shown to benefit vertical power production as reported through force plate analyses (Garhammer 1980, Stone 1993, Haff 2001), correlational analyses (Carlock, Smith et al. 2004), and various training interventions (Hoffman, Cooper et al. 2004, Tricoli, Lamas et al. 2005, Hawkins, Doyle et al. 2009). Garhammer (1980) demonstrated large values of peak power production in elite weightlifters with ranges between 1853 W to 4807 W for snatch and 2206 W to 4758 W for clean across weight-classes. These findings may be compared to values of 5377.8 ± 228.2 W, 4906.2 ± 222.1 W, and 3737.7 ± 193.6 W reported during countermovement vertical jumping of trained weightlifters and sprinters and untrained controls respectively (McBride, Triplett-Mcbride et al. 1999). Despite some discrepancy in peak power observed between movements, nearly perfect correlations have been reported between the squat jump and snatch (r=0.92), squat jump and clean and jerk (r=0.90), countermovement jump and snatch (r=0.93), and countermovement jump and clean and jerk.
(r=0.91) in national and international calibre male weightlifters (Carlock, Smith et al. 2004).

Training investigations by Tricoli et al. (2005), Hoffman et al. (2004), and Hawkins et al. (2009) all reported a direct benefit of weightlifting training on vertical power production. Both Hoffman et al. (2004) and Tricoli et al. (2005) reporting significant gains in vertical jump performance. Tricoli et al. (2005) reported a percentage change of 9.5% for squat jump and 6.6% for countermovement jump following 8 weeks of training with the power clean in resistance trained men. Hawkins et al. (2009) demonstrated significant gains in both squat and countermovement jump power with 8 weeks of weightlifting training in college-aged males; with pre- to post- increases of 9.8% and 12.1% respectively. Considering the vertical power produced by elite weightlifters, the correlation between vertical jump performance and weightlifting results, and the demonstrated ability of weightlifting to enhance vertical power production, it is clear that training with these movements (e.g. power clean) benefits the athlete’s ability to produce vertical power. Since strong evidence exists for the relationship between vertical power production and sprint start performance; and weightlifting training has been demonstrated to benefit vertical power production, it is intuitive that weightlifting training will directly benefit sprint start performance.

**Weightlifting to Benefit Horizontal Power Production.** A dearth of information examining the relationship between weightlifting training and horizontal power production currently exists. From the handful of published works, McGuigan and Winchester (2008) reported a not significant relationship between power clean and standing broad jump performance in Division I collegiate football players. Supporting these findings, Barr et al. (2014) reported a negative correlation (r=-0.44) between changes in power clean and standing broad jump performance over a year of training in international rugby athletes. While these preliminary findings suggest weightlifting training as ineffective in the development of horizontal power production, they must be viewed with caution due to a sparse amount of available data and the several studies (Delecluse, Van Coppenolle et al. 1995, Baker and Nance 1999, Tricoli, Lamas et al. 2005, Cormie,
McGuigan et al. 2010) that support vertical power training as a means to develop sprint performance (i.e. a separate largely horizontal movement).

Weightlifting to Benefit Sprint Start Performance. Multiple investigations have provided direct evidence for the benefits of weightlifting training on sprint start performance. Tricoli et al. (2005) performed the initial training investigation demonstrating significant gains in peak horizontal 10 m sprint velocity after 8 weeks of training with the power clean. Further to this, Hori et al. (2008) determined a negative correlation between 1RM hang power clean and 20 m sprint time in semi-professional Australian rules football players. These findings were further supported by Comfort and Pearson (2014), who determined a negative correlation between power clean performance and both 5 m and 10 m sprint start times in professional rugby league players. The relationship between weightlifting training and sprint start performance has recently been expanded with Chaouachi et al. (2014) reporting a large effect of snatch and clean training on 5 m sprint performance in naïve youths (ages 10-12). While the literature clearly supports the ability of weightlifting training to improve dry-land sprint start performance, the effects of weightlifting training on STSS start performance are currently unknown. Should the STSS start be demonstrated as kinetically and kinematically equivalent to the dry-land sprint start as current evidence suggests, then future research should seek to directly quantify the effects of training with the weightlifting movements on STSS start performance.

Specific Power Adaptations Elicited by weightlifting. Power production capabilities are often quantified through vertical jump performance with peak displacement identified as the outcome variable. Displacement is determined entirely by the height of the centre of mass (COM) and the vertical velocity at toe off (Moir 2008). While increasing COM height when the toes leave the ground (i.e. at toe off) will improve displacement, the practical ability to do so is confined within a limited range leaving vertical velocity at toe off as the precedent variable (Dapena and Ficklin 2007). Vertical velocity is entirely dependent on vertical impulse (Ohanion 1985), thus, any means of improving area under the force-time curve will likely result in vertical jump performance improvement.
Weightlifting training is known to positively affect impulse over multiple sections of the force-time curve including rate of force development (Häkkinen, Komi et al. 1987, Häkkinen and Myllylä 1990, Haff, Carlock et al. 2005), peak force (McBride, Triplet-Mcbride et al. 1999, Haff, Carlock et al. 2005), and peak power (McBride, Triplet-Mcbride et al. 1999, Hawkins, Doyle et al. 2009). Being able to sub-divide impulse into specific areas is important as it provides insight into the location of change elicited by the training stimulus. Currently, only RFD, peak force, and peak power have been examined as areas of change resulting from weightlifting training.

Supporting the influence of weightlifting training on RFD are the high absolute values produced by both elite male (Häkkinen, Komi et al. 1987) and female (Haff, Carlock et al. 2005) weightlifters in combination with comparative literature demonstrating greater RFD capabilities of power trained athletes as compared to endurance and untrained individuals (Häkkinen and Myllylä 1990). Additionally, Häkkinen et al. (1990) reported on the ability of short-term power training to improve RFD in physically active women with time to reach 500 N decreasing from 161 ± 107 ms to 93 ± 65 ms over 16 weeks as evaluated by an isometric squat-type movement. McBride et al. (1999) has demonstrated greater peak force outputs during vertical jumping for trained weightlifters as compared to trained powerlifters, trained sprinters, and untrained individuals. Lending further support to the ability of weightlifting training to affect peak force is the moderate correlations reported between vertical jump performance and weightlifting performance in elite female weightlifters (r=0.53 to r=0.63 for peak force/kg versus SJ and CMJ respectively) (Haff, Carlock et al. 2005). Finally, weightlifting is known to improve peak power production during vertical jumping with Hawkins et al. (2009) showing improvements in peak power production with eight weeks of weightlifting training in untrained college aged males. While the effect of weightlifting training on these defined areas of the force-time curve are known, there are potentially other areas still unexplored.

One area still remaining to be explored is how weightlifting training impacts impulse over the end range of motion (ROM). No studies have directly explored this area with only one investigation (Arabatzi and Kellis 2012) identifying a possible mechanism by which weightlifting may function to
influence force production during this period. Arabatzi et al. (2012) demonstrated changes in knee co-activation patterns following 8 weeks of weightlifting training in untrained men suggesting a more optimal timing of knee deceleration during vertical jump performance, but these authors did not report on any indicators of end ROM kinetic change. While the effects of knee co-activation strategies on end ROM kinetic variables are currently unknown, previous works suggest optimal vertical jump strategies as void of all lower limb deceleration (Pandy, Zajac et al. 1990) and paradoxically that even trained jumping athletes demonstrate deceleration during ground contact across all lower limbs (Bobbert and van Ingen Schenau 1988). Thus, while the effects of weightlifting training on knee extensor co-activation are known, the overall effects on impulse over the end ROM as well as the deceleration strategies of the other lower body joints are currently unknown.

*Learning the Weightlifting Movements.* While the body of evidence supports the weightlifting movements as capable of developing vertical power production and influencing sprint start performance, these benefits have not yet been reconciled with the potentially steep learning curve necessary to gain movement proficiency (Vorobyev 1978, Baker 1991, Takano 1992). Sport coaches often criticise the weightlifting movements as a means for enhancing athletic performance because of the extended period of time they may take to learn before physical benefits can be observed (Medvedev 1989, Baker 1991). Considering the efficacy of a training modality must factor in the associated costs, training with the weightlifting movements cannot truly be considered viable until the learning process as well as the time to power production benefit has been quantified. The weightlifting movements undoubtedly require long learning timeframes to reach expertise due to the complexity of the movement patterns; this pertains to the number of joints utilized and thus the magnitude of muscular coordination necessary (Garhammer 1984, Burgener, Bielik et al. 1989). The lifts as competed with in the Olympic Games are considered total body exercises and require the utilization of most major muscle groups. Adding an additional layer of complexity to movement coordination are the limited time frames in which joint coordination must occur under appreciable movement velocities (Chernyak, Povetkin et al. 1982, Harbili 2012). Yet another factor
influencing the learning curve is the complex kinematic sequencing inherent to the so-called “double knee bend” in which the lifter is forced to drive vertical barbell velocity through hip extension while simultaneously flexing the knees and ankles (Vorobyev 1978, Enoka 1979). Considering the vast majority of lower body movement patterns utilized in sport require only coordinated extension of all three joints (de Koning, de Groot et al. 1989, de Koning, de Groot et al. 1991, Slawinski, Bonnefoy et al. 2010) the weightlifting pulls are considered some of the most technically complex movements in sport and thus difficult to master.

Although reports from the coaching literature outline timeframes increasing levels of technical mastery (Medvedev 1989, Baker 1991), no works have systematically quantified the time investment required to achieve a power benefit in elite athlete populations. To determine whether learning the weightlifting movements is worth the athlete time-resource investment, the first relevant question must address the time commitment necessary to obtain initial power benefit as well as the expected magnitude of benefit to performance. Once this initial investment is understood, the research focus must turn to the long-term benefits of weightlifting learning and training on vertical power production.

While weightlifting training has been indicated to benefit vertical power production, and both directly and indirectly shown to affect sprint start performance, advocating training with the weightlifting movements for the purposes of developing start performance in naive short track speed skaters is nonetheless irresponsible until the investment necessary to achieve gains is quantified. Considering that other intuitive dry-land training modalities may be capable of both directly benefitting the 500 m start (i.e. dry-land sprint start training) and vertical power production (i.e. vertical jump training), further systematic cost-benefit analyses should be performed on the weightlifting movements to determine if the overall benefits on performance justify the significant up-front time investment.

**Conclusion**

While previous investigations have indicated a relationship between start performance and elite 500 m STSS race outcome, no works have provided
direct examination utilising a data set from multiple years of elite competition. While these previous works as well as anecdotal information from the international skating community suggest a relationship, further work is necessary as the magnitude of relationship is poorly understood. Should a large relationship between start and race outcome be reported, being able to effectively train the start off-ice would be of benefit as it frees up ice time for allocation to other training needs. Considering transfer of training principles and potential similarity in movement mechanics, the dry-land sprint start may be a worthwhile dry-land start training means. While previous works have reported similarity between the pre-klapskate long track speed skating start and dry-land sprint start, further investigation utilising short track speed skaters and providing more detailed kinetic and kinematic quantification is necessary, since the klapskate dramatically changed the mechanics of speed skating. Should strong equivalence be reported, investigation into the direct effects of dry-land start training on short track start performance is necessary as no previous topical works utilizing long or short track skaters currently exist. Should dry-land sprint training be demonstrated to improve short track start performance, then weightlifting training should also be considered as a worthwhile off-ice means to develop short track start performance as the literature strongly reports the ability of weightlifting to develop dry-land start performance. Included in this analysis should be the initial learning investment necessary to reach performance benefit with the lifts as this topic has only been poorly explored in recreationally trained athletes and systematically unquantified in elite athlete populations. Considering the complex nature of weightlifting, initial investment may be longer as compared to other off-ice means also demonstrated to improve sprint performance. Finally, while the literature has explored specific areas of vertical power production affected by weightlifting training, other areas such as end range of motion kinetics are currently under-investigated yet important, as differences in this area may provide insight into the mechanisms by which weightlifting functions and may serve to separate weightlifting as an off-ice short track start training means.
Before applying interventions that aim to improve start performance, the importance of the start on international 500 m race outcome must first be established. Thus, the purpose of this investigation is to quantify the relationship between start performance and race outcome in elite 500 m short track speed skaters. While it appears likely that performance from start to entering first corner is a relevant variable in determining race outcome, this has not been demonstrated systematically nor has a relationship been quantified.
The Relationship Between Start Performance And Race Outcome In elite 500 m Short Track Speed Skating

IN PRESS- *International Journal of Sports Physiology and Performance*
Introduction

Short track speed skating is an Olympic sport generally requiring four to five competitors to race simultaneously around an oval track 111.11 m in length with advancement through competitions primarily determined by finish relative to competitors within the same heat (ISU 2012). Of the internationally contested distances, the 500 m is the shortest, and considered the sprint distance with elite races usually lasting 40 to 44 s for men and below 43 to 46 s for women (ISU 2012). While the 500 m shares overall similarity in race length and duration with other sporting events such as the athletics 400 m, current evidence suggests the within-race strategy and thus overall allocation of energy resources between disciplines exhibits a marked dichotomy (Maw, Proctor et al. 2006, Hart 2007, Hanon and Gajer 2009).

The rules of short track speed skating in conjunction with the physics of racing at high speeds over a tightly cornered oval track dictates difficult overtaking conditions across short track events (Rundell 1996, Bullock, Martin et al. 2008) with increased difficulty during the 500 m due to the maximal sprint nature of the event (Maw, Proctor et al. 2006, Bullock, Martin et al. 2008, Muehlbauer and Schindler 2011). Considering there are limited efficient routes or “tracks” around the short track course that maximize speed and limit overall distance travelled, competitors must generally travel in series or skate a less efficient parallel route thereby increasing the risk of premature fatigue. This need to skate in series is most apparent over the apex of the track corner where overtaking generally does not occur during 500 m races (Ji, Ji et al. 2000, Lee, Back et al. 2006, Bullock, Martin et al. 2008). The elimination of overtaking over the corner apex results in finite passing windows unique to 500 m short track competition. Where in other sporting events overtaking can occur over extended periods of time, in the 500 m complete passes of opponents must take place within approximately 3 s or 35 m windows, spanning the exit of one corner to the entrance of the next (ISU 2012).

Difficulty in overtaking during the 500 m distance places a premium on rank position entering first corner (RPEFC); i.e. starting fast. This relationship between start and overall race performance has been indicated by Maw et al.
(2006) and later confirmed by Bullock et al. (2008) with 71% of eventual winners in the men’s events leading the race after the initial half lap with no winners coming from outside of second place at the half-lap time point. Both Maw et al. (2006) and later Muehlbauer and Schindler (2011) reported significant Kendall’s tau rank correlations between starting grid position and 500 m race outcome, suggesting start performance is of such importance that being slightly closer to the first block due to the geometry of the start line in relation to the first corner provides a statistical advantage at the international level for both men and women. While previous works have greatly aided topic exploration, gaps in understanding still exist as no works have directly investigated the relationship between RPEFC and race outcome utilizing a robust, elite level data set. Therefore, the purpose of this investigation was to systematically examine the relationship between RPEFC and 500 m race outcome at the international level for both men and women. To further increase depth of understanding, this study also intended to examine the change in relationship with competition round (e.g. quarter-vs. semi-final) and absolute race intensity.

**Methods**

The data were compiled from video footage available from the International Skating Union website (www.ISU.org) (ISU 2012) and youtube.com© (youtube.com 2014). Ethics approval was not necessary as all data is publicly available and no athlete interactions were required. Data analysed included only quarter-final, semi-final, and final races of the men’s and women’s 500 m event from ISU World Cups from the 2011-2012 (6 events) and 2013-2014 (4 events) seasons, and 5 of 6 World Cup events from the 2012-2013, the first World Cup of this season was omitted due to video footage not being available. Races were also included from the 2010 and 2014 Olympic Winter Games. To protect the investigation’s validity, races with less than 3 skaters were omitted (1 race) and only races without a fall or disqualification were included in analysis; thus 124 total races were omitted from the data set. A fall in this context was defined as contact between body and ice with a corresponding loss of contact between both
skate blades and ice. This resulted in the analysis of 896 data points; 440 for men and 456 for women.

Start performance was determined as skater rank position through the first block of the first corner. First block of first corner was chosen as the criterion for starting performance as the distance provides a clear visual marker which coincides with the shift in the speed skating stroke from start mechanics dominated by fixed point rearward force application to the traditional gliding motion prevalent throughout short track speed skating racing (de Koning, de Groot et al. 1989, de Koning, Thomas et al. 1995). Using a publicly available spreadsheet (Wessa 2012) Kendall’s tau test for rank correlations were used to determine the relationship between RPEFC and race outcome for each race and as a further sex specific analysis.

To understand how the relationship between RPEFC and race outcome changes with level of competition progression in both sexes, Kendall’s tau rank correlations were compared between successive tournament rounds: quarterfinals, semi-finals, B-final, A-final. To provide an indication of how the relationship between RPEFC and race outcome changes with absolute race speed, each individual race was ranked by absolute winning time from fastest to slowest versus the other races within the same World Cup or Olympic event in each sex respectively with Kendall’s tau rank correlations compared between rankings. Within-event ranking allowed for control over differences in absolute times between events attributed to variance in ice and environmental conditions. Correlations were classified in accordance with Hopkins (2006) and adjusted according to Gilpin (1993) as follows: trivial (T<0.07), small (T=0.07–0.20), moderate (T=0.20–0.34), large (T=0.34–0.50), very large (T=0.50–0.72), and nearly perfect (T>0.72).

**Results**

Overall the athlete leading at the first block of the first corner after starting won the race 154 times out of 222 opportunities while the athlete second to the first block won the race 43 times (Figure 7A). This same trend was present regardless of sex (Figure 7B men and 7C women) and strength of the finishing order appears to hold for the athlete in 4th position to the first
block finishes the race in 4th position. The tau rank correlation for RPEFC and 500 m race outcome was significant (T=0.60; p<0.0001) and remained significant for each sex (men: T=0.53; p<0.0001 and women: T=0.66; p<0.0001). Data was additionally analysed considering only four skater races (cohort: T=0.59; men: T=0.52; women: T=0.66; p<0.0001), four and five skater races (cohort: T=0.59; men: T=0.53; women: T=0.66; p<0.0001), and three and four skater races (cohort: T=0.59; men: T=0.52; women: T=0.66; p<0.0001). Considering the equivalence in relationship strength between each subset and the full data set (i.e. three, four, and five skater races), all subsequent results are reported from the entire data set. When considered by event progression (quarter-, semi-, B-, and A-finals), a significant (p<0.0001 for all rounds) relationship for men was observed (T=0.57, T=0.46, T=0.50, and T=0.53 respectively) while for women a significant (p<0.0001 for all rounds) relationship was determined (T=0.68, T=0.67, T=0.53, and T=0.73 respectively; Figure 8). Shown in Figure 9, both men (A) and women (B) appeared to exhibit a tendency towards increasing the strength of relationship between RPEFC and race outcome with absolute race intensity (men: p<0.0001 to p=0.04; fastest race: T=0.61, 2nd fastest: T=0.65, 3rd fastest: T=0.43, 4th fastest: T=0.51, 5th fastest: 0.40, 6th fastest: T=0.45; 7th and 8th fastest combined: T=0.46; women: p<0.0001 to p=0.002; fastest race: T=0.76, 2nd fastest: T=0.66, 3rd fastest: T=0.71, 4th fastest: T=0.67, 5th fastest: 0.59, 6th fastest: T=0.54; 7th and 8th fastest combined: T=0.55).
Figure 7. A frequency distribution relating rank position entering first corner (RPEFC) with overall 500 m race outcome A) for the entire cohort; B) for men; and C) for women.
Figure 8. The relationship between rank position entering first corner (RPEFC) and 500 m race outcome with progressive competition round from quarterfinals through A-finals for A) men; and B) women. Trend line represents line of best fit of the data.
Figure 9. The relationship between rank position entering first corner (RPEFC) and 500 m race outcome with absolute race intensity for A) men; and B) women. As an indirect measure of absolute race speed, races were ranked from fastest to slowest within each event. Trend line represents line of best fit of the data.
Figure 10. Average absolute difference in race time between winning A-final and average quarterfinal time for two series of four seasons of international 500 m competition spaced a decade apart for A) men and B) women. Trend lines represent lines of best fit for each data set.

Discussion

A major finding of this investigation is the very large quantifiable magnitude of relationship between rank position entering first corner (RPEFC) and race outcome in international 500 m short track speed skating competition. Previous investigations (Maw, Proctor et al. 2006, Bullock, Martin et al. 2008, Muehlbauer and Schindler 2011) established the start as a relevant competition factor, this investigation quantifies the magnitude of
importance. The strength of tau rank correlations for overall (τ=0.60), men (τ=0.53), and women (τ=0.67), explaining 28% of the variance in race outcome for men, and 45% for women, provide substantial evidence for the importance of RPEFC. While the international short track speed skating community has traditionally recognized the start as a relevant factor in determining 500 m race outcome, it is possible the gravity of importance has not been properly understood.

Although the exact magnitude between RPEFC and 500 m race outcome may be larger than expected for women, upon deeper consideration the outcome is intuitive but may also be an unreported representation of the depth of international women’s 500 m field. As a performance factor, the importance of the start has been advocated as overtaking during international 500 m competition is known to be difficult (Ji, Ji et al. 2000, Lee, Back et al. 2006, Maw, Proctor et al. 2006, Muehlbauer and Schindler 2011) with Bullock et al. (2008) reporting an average of only 4 total passes per 500 m race during a season of World Cup and World Championship competition. Difficulty in overtaking during elite 500 m competition may be attributed to the short duration of the race versus the longer 1000 m and 1500 m events (Rundell 1996), the close to maximal speeds sustained by most competitors across the entirety of a race, the finite overtaking windows created by the shape of the speed skating track, and the rules of short track which prohibit contact during overtaking and tend to favour the lead skater (ISU 2012). While a maximal effort from the start may be the optimal pacing strategy in all sprint events under 80 s (van Ingen Schenau, de Koning et al. 1994), this strategy may be more important during short track as claiming a lead position at the start may be easier than overtaking an opponent during the remainder of a race. While the start may be delineated as the initial 2-3 s of a race, competitors start each race almost in parallel (Maw, Proctor et al. 2006). This is in contrast to the majority of the race where efficiency dictates competitors skate mostly in series. Thus, overtaking during the start is advantageous as the overtaking competitor is in an almost neutral parallel position as opposed to completely behind. Furthermore, no skater is deemed to be leading at the start, so it may be
easier to jockey for position with significantly less risk of disqualification than during a top speed overtaking attempt.

The concept of start performance as a tie-breaker for closely matched skaters was originally put forth by Maw et al. (2006), who reported starting grid position as a larger determinant of race outcome with progressive competition round. Their findings suggest as tournament rounds progress and weaker skaters are eliminated, the pool of remaining athletes display greater homogeneity in performance characteristics. This dictates the ability to achieve a lead position from an approximately neutral position, i.e. starting fast, as a more relevant performance determining variable. Our investigation did not find a change in RPEFC-race outcome relationship with competition round (Figure 8); however, this may be explained by increases in the strength of field at the international level over the decade between studies. We propose that during current competition, by quarterfinal races athletes already tend to display similar top speeds and speed endurance capabilities. The results of our investigation nonetheless support the “tie-breaker” concept as we report the relationship between RPEFC and race outcome as larger with absolute race intensity (Figure 9). It is likely that as elite performers become more homogenous and speed endurance capabilities are approached, skaters can no longer distinguish performance through these characteristics and therefore must utilize the start as a means to seize a lead position. 

To verify increased parity in level of competition by quarterfinal over the decade between studies, we compared the average difference between average quarterfinal and A-final times. Races compared were from four World Cup seasons from 2000-2004 and 2010-2014 (Figure 10). For men and women the discrepancy between average winning quarterfinal race time and winning A-final time was larger in the years 2000-2004 than they were for 2010-2014. It is also apparent across the two quadrennials analysed that both sexes exhibit a clear trend towards increased quarterfinal race pace relative to A-final race pace. This not only demonstrates increased parity in 500 m quarterfinal competition level between investigations, but also shows many of the relevant years over which strength of field increased. A
limitation across the investigation is that starting grid positions are seeded in quarterfinals through to A-Finals. A minor, but reportable statistical advantage is known to inside starting grid position (Maw, Proctor et al. 2006, Muehlbauer and Schindler 2011), which gives faster skaters a potential advantage in achieving a lead position post-start. Since it is likely these skaters are faster due to superior top speeds, speed endurance capabilities, and overtaking skills, it is possible they would find their way to a first place finish, even if they were not leading after the start. Despite this limitation, current parity in race speed at the international level and the existent relationship between RPEFC and 500 m race outcome indicates that training the start will benefit 500 m results.

**Practical Applications**

Our findings strongly advocate prioritization of start training for skaters looking to improve 500 m results; however, they must be considered within the context of an entire training program. While training the start may lead to better 500 m results, the 500 m is only one of potentially four events raced by elite skaters and the start has only been robustly demonstrated to benefit a single event. In addition to prioritizing the start versus other training needs, programming must also consider the specific needs of the individual skater. For the majority of skaters capable of producing world class absolute race times (e.g. quarterfinal level skaters) improving RPEFC may serve as the tie-breaker in determining race outcome. In addition to this generalization, skaters with poor start performances, below average overtaking skills, and exceptional blocking capabilities may particularly benefit from start training. Conversely, skaters with either exceptionally strong or weak top speed and speed endurance capabilities, strong or well developed start abilities, and skaters particularly gifted at overtaking may not benefit greatly from developing 500 m RPEFC.

**Conclusion**

The start is a performance determining variable in elite 500 m short track speed skating race outcome. While previously understood in generality, the magnitude of relationship was unknown and potentially underestimated
considering the high tau rank correlations observed. Importantly RPEFC potentially serves as a tie-breaker, likely because the peculiarities of short track make overtaking during 500 m competition difficult, thus neutralizing small advantages skaters may hold in top speed and speed endurance characteristics. Furthermore RPEFC becomes increasingly important as absolute race pace increases which is intuitive as the challenges associated with overtaking become magnified with increasing race intensity. While RPEFC is an important factor in 500 m race outcome, the prioritization of start training within the overall programming of athletes must consider both overall training priorities and the needs of the individual skater. Considering the effect of absolute race time on the relationship between RPEFC and race outcome and the skillset necessary for successful 500 m performance, it is likely skaters with high top speeds, high speed endurance capabilities, poor overtaking skills, excellent blocking skills, and poor starting capabilities will particularly benefit from the prioritization of start training.
CHAPTER FOUR
The importance of start performance in elite 500 m race outcome as reported in Chapter 3 supports the prioritization of start training within elite environments. Considering potential limitations to on-ice time and monotony of current start training practices, training the start on dry-land would be of benefit. Potential similarities between dry-land sprinting and start performance demonstrated in long track speed skating (de Koning, de Groot et al. 1989, de Koning, Thomas et al. 1995) suggest benefits of dry-land start training on STSS start performance; however, this relationship has not been directly quantified. Thus, the purpose of the following investigation is to perform a direct kinematic comparison between the short track speed skating and dry-land sprint start.
A Lower Body Kinematic Comparison Of The Short Track Speed Skating Start And Dry-Land Sprint Literature

SUBMITTED- Sports Biomechanics
Introduction

International 500 m short track speed skating (STSS) race outcome has been observed to co-vary with start performance as indicated by large Tau correlations (Men: $\tau=0.53$ and Women: $\tau=0.67$) between skater position entering first corner and race outcome (Haug, Drinkwater et al. 2015). This direct observation and previous works reporting a significant relationship between starting grid position and race outcome (Maw, Proctor et al. 2006, Muehlbauer and Schindler 2011) highlight the importance of starting fast and indicate the start as a relevant area of training focus.

The pre-klapskate long track speed skating start has been well defined with lower body joint angles, sagittal plane horizontal velocities, lateral deviations of the centre of mass, skate blade push-off angles, and transverse plane skate paths over the elite 500 m start reported (de Koning, de Groot et al. 1989, de Koning, Thomas et al. 1995). This pre-klapskate long track speed skating start was identified as equivalent to a dry-land sprint start, characterized by fixed-point rearward directed force applications transitioning to the gliding motion typically associated with speed skating (de Koning, de Groot et al. 1989, de Koning, Thomas et al. 1995). While these findings are robust, they are specific to the long track start leaving the body of literature void of kinematic analyses specific to the STSS start. This distinction may be important as the STSS and pre-klapskate long track start may deviate due to the differences in equipment set up (i.e. rocker, curve, and positioning of blade) and track shapes between disciplines.

Considering this dearth of information specific to the STSS start, the purpose of this investigation was to provide a robust, kinematic comparison between the STSS start, defined as the time taken from start to first corner (14.43 m) of the 500 m event, and the dry-land sprint start literature in elite athletes. Establishing kinematic similarity between surfaces is important as it may provide substantial evidence of a potential transfer of training effect (Zatsiorsky and Raitsin 1974, Bondarchuk 2007, Bondarchuk 2010) between the dry-land start and STSS competition start. Considering the STSS start is traditionally trained on-ice and ice time may be a limited resource, even in elite environments, being able to train the start on dry-land
would create greater athlete programming flexibility as well as a novel training stimulus.

Methods

Participants. Athletes were recruited from the Australian National Short Track Speed Skating and Developmental Program (5 men and 1 woman) to participate. Athletes’ physical characteristics were $20.5 \pm 3.4$ y, $176.6 \pm 8.7$ cm, $68.9 \pm 10.3$ kg, with $9.0 \pm 4.2$ y STSS training experience. All athletes were free from injury at the time of testing and were all in a technique specific training phase. Each athlete provided informed consent prior to participation and the investigative cohort represented the total number of internationally competitive STSS athletes available. The Australian Institute of Sport and the Charles Sturt University Human Research Ethics Committees both approved this investigation.

Testing. On-ice testing was performed in a standard Olympic-sized ice hockey rink; while dry-land sprints were performed on an indoor court with a suspended wood floor surface 24 h prior to on-ice testing. Regardless of testing surface, prior to beginning an individual warm up each athlete was marked-up using white semi-reflective adhesive tape placed on selected anatomical landmarks on the right hand side on the body, head of the greater trochanter, lateral epicondyle of the femur, and lateral malleolus of the ankle. After a thorough self-selected warm up consisting of light jogging, dynamic stretching and submaximal sprint efforts, each athlete completed two (2) standardized sub-maximal 14.43 m efforts 10-15 minutes in duration from a competition standing start position (2-point stance) at an increasing intensity of approximately 70% and 85% effort. Athletes then performed two (2) maximal efforts with a minimum of 5 minutes rest between efforts. The distance of 14.43 m was chosen as it reflects the official mean distance from start line to first block in the 500 m event of 14.425 m and was the distance that we were able to accurately measure. Regardless of surface each maximal effort sprint was timed using electronic timing gates (Swift Performance Equipment, Carole Park QLD, Australia). Timing gates were set perpendicular to the linear plane of motion, and gates were positioned at start (0 m) and 14.43 m. During dry-land testing, athletes were instructed to
use a two-point start position and for on-ice testing athletes were instructed to execute a start position and start movement equivalent to that performed during competition (two-point position). High-speed video (Photron Fastcam MC2, Photron Ltd, San Diego USA) footage was obtained for each on-ice maximal effort sprint. 5 synchronised cameras sampling at 125 Hz, with 512 x 512 pixel resolution were positioned such that one camera was capturing in the frontal plane (primary temporal variables) and four cameras were in the sagittal plane (primary kinematic variables) at approximately 60° to the plane of movement so that each marker was captured by at least two cameras simultaneously at all times (Figure 11). Calibration of the static movement space was performed using a known 2.0 m reference pole with reflective tape markers at 0.5 m distances, to form a 2.0 m³ calibrated space. Anatomical landmarks from each camera view were digitised using ProAnalyst (ProAnalyst; Xcitex Inc, Cambridge, MA, USA). Markers were tracked from initial movement until the fourth ground contact or when the athlete when out of frame using ProAnalyst software (Xcitex, Cambridge MA, USA). Digitised trajectory data were then transformed into 3-D space within ProAnalyst and resultant joint angles calculated in ProAnalyst (ProAnalyst; Xcitex Inc, Cambridge, MA, USA). Resultant ankle, hip, and knee joint angles were calculated over the course of the standing start and first full stride.

Data analysis. All kinematic data was recorded and analysed for the right leg only. The athlete group was homogenous in regards to the first ground contact, being made with left blade at all times. The left leg was not analysed due to an inability to place a wired camera system in the center of the rink. The standing start push off was defined as the initial lower body extension by the rear leg (i.e. right leg) plus the first ground contact (i.e. the left leg), here forth referred to as the jab step (Figure 12). These two steps were collectively identified as the standing start push off as they best approximate bilateral force application during the sprint block phase and initial motion from a 2-point dry-land sprint start stance. The first full stride was defined as the period between ground contact following the standing start (i.e. left leg flight following the jab step) and the subsequent ground contact with the same (i.e. left) leg (Figure 12). Right leg hip and knee joint
kinematics were extracted using a ProAnalyst (Xcitex Inc, Cambridge, MA) and analysed by absolute time. Foot contact and flight times were determined by frame by frame visual inspection of the raw video files. The initial jab step and first six ground contacts (i.e. blade-surface interaction time) on-ice and the first six contacts on land were analysed for timing only. The flight between the jab step and first contact as well as the first five flight times on-ice, and first five flight times on land were analysed. These parameters were chosen as they represent the maximum number of contacts and flights all athletes achieved over the 14.43 m distance. Three of six athletes commenced the dry-land sprinting motion with a jab step and three began with bilateral force application traditionally associated with dry-land sprinting. Due to this mixed data, the dry-land jab step and associated flight time were omitted from the analysis.

Raw trajectory data were smoothed using a low pass 4th order Butterworth filter routine with an 18 Hz cut off frequency, with the frequency determined from a residual analysis according to Winter (p42) (1990).

**Statistics.** Descriptive statistics are reported as group mean ± SD except where otherwise noted. To perform an inferential kinematic comparison between surfaces, we conducted independent t-tests between our data and the findings of Murphy et al. (2003) and Debaere et al. (2013) these authors reported kinematic data on two-point field sprints and three-point athletics sprints, respectively, with the use of a publicly available spreadsheet (GraphPad 2015). Magnitude-based inferences on the differences in ground contact and flight times for the first seven contacts were compared intra-athlete between surfaces (i.e. ice and dry-land) by dependent t-test. For each variable, qualitative descriptors of the standardized effects were described using these criteria: trivial < 0.2, small 0.2-0.5, moderate 0.5-0.8, large >0.8 (Cohen 1988). Effects with confidence limits overlapping the thresholds for small positive and negative effects (exceeding 0.2 of the standard deviation on both sides of the null) were defined as unclear. Effects with confidence limits that did not overlap the defined thresholds for clear small or large effect sizes were defined as substantial (Liow and Hopkins 2003). The 95% confidence limits (CL) for each variable are used to define the range representing the uncertainty in the true value of the
(unknown) population mean or the precision of estimates. To compare individual on-ice and dry-land sprint start times, an intra-athlete correlation was conducted between surfaces. Correlations were classified in accordance with Cohen (1988) and adjusted by Hopkins (2006) as follows: trivial ($r<0.10$), small ($r=0.10–0.29$), moderate ($r=0.30–0.49$), large ($r=0.50–0.69$), very large ($r=0.70–0.89$), and nearly perfect ($r≥0.90$).

**Figure 11.** Schematic representation of the data collection set-up (not to scale) with filled triangles representing infra-red light gates, small filled circles representing the calibration spaces utilized and the shaded triangles demonstrating the focal areas for each Photron camera.

**Figure 12.** The short track speed skating (STSS) standing start. Photos demonstrate: start position, peak extension of the standing start, peak flexion of the standing start, peak extension of the first stride, peak flexion of the first stride; respectively.
Results

The athletes demonstrated maximum sagittal plane hip and knee angles of 153.7 ± 7.9° and 137.9 ± 7.8° during toe off of the standing start push off with minimum hip and knee angles of 85.1 ± 9.6° and 64.8 ± 7.0°, with an effective ROM for the hip and knee of 67.7 ± 7.9° and 73.1 ± 3.2°, respectively (Table 3 and 4). As compared to sub-elite sprinters (Debaere, Delecluse et al. 2013), there was no difference in maximum hip and knee angles and minimum knee angles during the standing start push-off with only minimum hip angle identified as different (ES=-0.85) via 95% confidence limits (Table 5). During the first full stride, athletes demonstrated maximum hip and knee angles of 148.3 ± 7.8° and 152.1 ± 11.6° at toe-off with minimum hip and knee angles of 91.5 ± 11.1° and 61.6 ± 8.7° during flight and ROMs of 56.8 ± 8.5° and 90.5 ± 17.3°, respectively (Table 3 and 4). As compared to trained field athletes (Murphy, Lockie et al. 2003) and sub-elite sprinters (Debaere, Delecluse et al. 2013), there was no difference in maximum knee angle during the first full stride, but differences in maximum hip angles were identified (ES=0.91 compared to fast group field athletes; ES=-1.55 compared to sprinters). As compared to trained field athletes (Murphy, Lockie et al. 2003), there was no difference for hip and knee range of motion (Table 5). Due to spatial calibration issues during the dry-land trials, kinematic data was not suitable for comparison analysis.

Ground contact occurred at 0.33 ± 0.06 s, 0.68 ± 0.07 s, and 0.95 ± 0.07 s for the first, second, and third on-ice contacts, respectively, and at 0.62 ± 0.09 s and 0.88 ± 0.12 s for the first and second dry-land contacts (matched to second and third on-ice contacts). The observed intra-athlete differences in contact (Table 6) and flight (Table 7) time across the first seven ground contacts were very large between surfaces with contacts times substantially shorter (ES=2.84-5.07) and flight times substantially longer (ES=2.11-6.87) on dry-land (Figure 13). The electronic timing system failed to record an on-ice start time for two athletes. The on-ice and dry-land start times (mean ±SD) were 2.69 ± 0.23 s and 2.50 ± 0.16 s respectively, with the
individual intra-athlete correlation between surface sprint times was $r=0.93$ ($p<0.001$) with the equation for line of best fit $y=0.64x+0.79$ (Figure 14).

Table 3. A description of mean (SD) hip (n=8 trials) and knee (n=7 trials) joint kinematics between the elite on-ice STSS Start (STSS Start) and the elite long track speed skating start with long track data referenced from de Koning et al. (de Koning, de Groot et al. 1989) on two elite long track speed skaters (n=1 trial).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Short Track</th>
<th>Long Track</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Start Phase</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximal hip angle (*)</td>
<td>153.7 (7.9)</td>
<td>~150-155</td>
</tr>
<tr>
<td>Maximal knee angle (*)</td>
<td>137.9 (7.8)</td>
<td>~165</td>
</tr>
<tr>
<td>Minimal hip angle (*)</td>
<td>85.1 (9.6)</td>
<td>~75-80</td>
</tr>
<tr>
<td>Minimal knee angle (*)</td>
<td>64.8 (7.0)</td>
<td>~55-60</td>
</tr>
<tr>
<td><strong>First Full Stride</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximal hip angle (*)</td>
<td>148.3 (7.8)</td>
<td>~150-160</td>
</tr>
<tr>
<td>Maximal knee angle (*)</td>
<td>152.1 (11.6)</td>
<td>~165</td>
</tr>
<tr>
<td>Minimal hip angle (*)</td>
<td>91.5 (11.1)</td>
<td>~85</td>
</tr>
<tr>
<td>Minimal knee angle (*)</td>
<td>61.6 (8.7)</td>
<td>~55-60</td>
</tr>
</tbody>
</table>
Table 4. A description of mean (SD) hip (n=8 trials) and knee (n=7 trials) joint kinematics between the elite on-ice two-point STSS start (STSS Start), and dry-land sprint starts in trained field athletes (n=20 trials) using a two-point start position (Two-Point Fast; Two-Point Slow) Murphy et al. (Murphy, Lockie et al. 2003) or sub-elite sprinters (n=60 trials) using a three-point start position Debaere et al. (Debaere, Delecluse et al. 2013) (Three-Point).

<table>
<thead>
<tr>
<th></th>
<th>Variable</th>
<th>STSS Start</th>
<th>Two-Point Fast</th>
<th>Two-Point Slow</th>
<th>Three-Point</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Start Phase</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximal hip angle (*)</td>
<td>153.7 (7.9)</td>
<td>146.8 (9.4)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximal knee angle (*)</td>
<td>137.9 (7.8)</td>
<td>134.9 (11.2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimal hip angle (*)</td>
<td>85.1 (9.6)</td>
<td>90.7 (6.6)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimal knee angle (*)</td>
<td>64.8 (7.0)</td>
<td>70.1 (10.2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hip range of motion (*)</td>
<td>67.7 (7.9)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee range of motion (*)</td>
<td>73.1 (3.2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>First Full Stride</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximal hip angle (*)</td>
<td>148.3 (7.8)</td>
<td>141.1 (7.9)</td>
<td>143.1 (7.0)</td>
<td>180.6 (20.9)</td>
<td></td>
</tr>
<tr>
<td>Maximal knee angle (*)</td>
<td>152.1 (11.6)</td>
<td>147.8 (9.8)</td>
<td>156.1 (9.5)</td>
<td>165.2 (20.6)</td>
<td></td>
</tr>
<tr>
<td>Minimal hip angle (*)</td>
<td>91.5 (11.1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimal knee angle (*)</td>
<td>61.6 (8.7)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hip range of motion (*)</td>
<td>56.8 (8.5)</td>
<td>52.5 (8.7)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee range of motion (*)</td>
<td>90.5 (17.3)</td>
<td>81.0 (8.9)</td>
<td>86.7 (18.1)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 5. 95% confidence limits (95% CL) and effects sizes (ES) for the difference in joint kinematics between the elite on-ice STSS start (STSS Start), and dry-land sprint starts in trained field athletes (n=20 trials) using a two-point start position (Two-Point Fast; Two-Point Slow) Murphy et al. (Murphy, Lockie et al. 2003) or sub-elite sprinters (n=60 trials) using a three point start position Debaere et al. (Debaere, Delecluse et al. 2013) (Three-Point).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Two-Point Fast</th>
<th></th>
<th>Two-Point Slow</th>
<th></th>
<th>Three-Point</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>95% CL</td>
<td>ES</td>
<td>95% CL</td>
<td>ES</td>
<td>95% CL</td>
<td>ES</td>
</tr>
<tr>
<td><strong>Start Phase</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max hip angle</td>
<td>-0.05 to 13.85</td>
<td>0.73</td>
<td>-5.72 to 11.72</td>
<td>0.28</td>
<td>-10.85 to -0.36</td>
<td>-0.85</td>
</tr>
<tr>
<td>Max knee angle</td>
<td>-13.24 to 2.6</td>
<td>0.52</td>
<td>-1.01 to 11.41</td>
<td>0.74</td>
<td>-47.27 to -17.33</td>
<td>-1.55</td>
</tr>
<tr>
<td>Min hip angle</td>
<td>-3.14 to 11.74</td>
<td>0.49</td>
<td>-13.08 to 5.08</td>
<td>0.42</td>
<td>-29.01 to 2.81</td>
<td>-0.64</td>
</tr>
<tr>
<td>Min knee angle</td>
<td>-1.34 to 11.74</td>
<td>0.49</td>
<td>-6.14 to 7.74</td>
<td>1.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>First Full Stride</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max hip angle</td>
<td>0.43 to 13.97</td>
<td>0.91</td>
<td>-1.01 to 11.41</td>
<td>0.74</td>
<td>-47.27 to -17.33</td>
<td>-1.55</td>
</tr>
<tr>
<td>Max knee angle</td>
<td>-5.00 to 13.580</td>
<td>0.44</td>
<td>-13.08 to 5.08</td>
<td>0.42</td>
<td>-29.01 to 2.81</td>
<td>-0.64</td>
</tr>
<tr>
<td>Knee ROM</td>
<td>-0.89 to 19.89</td>
<td>1.07</td>
<td>-12.40 to 20.00</td>
<td>0.21</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 6. Differences in contact times (mean ± SD) for first seven full strides of the on-ice and dry-land sprint start in short track speed skating athletes (n=6), with certainty of the estimate shown with a confidence limit (95% CL) and a magnitude of the difference indicated by an effect size (ES).

<table>
<thead>
<tr>
<th>Step Number</th>
<th>Mean (SD) Contact Time On-Ice</th>
<th>Mean (SD) Contact Time On Land</th>
<th>95% CL</th>
<th>ES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.32 (0.04)</td>
<td>0.20 (0.04)</td>
<td>-0.15 to -0.08</td>
<td>3.27</td>
</tr>
<tr>
<td>2</td>
<td>0.27 (0.03)</td>
<td>0.18 (0.04)</td>
<td>-0.11 to -0.06</td>
<td>2.84</td>
</tr>
<tr>
<td>3</td>
<td>0.26 (0.03)</td>
<td>0.17 (0.02)</td>
<td>-0.12 to -0.08</td>
<td>2.96</td>
</tr>
<tr>
<td>4</td>
<td>0.25 (0.02)</td>
<td>0.15 (0.01)</td>
<td>-0.12 to -0.09</td>
<td>4.49</td>
</tr>
<tr>
<td>5</td>
<td>0.27 (0.02)</td>
<td>0.15 (0.01)</td>
<td>-0.13 to -0.11</td>
<td>5.70</td>
</tr>
<tr>
<td>6</td>
<td>0.27 (0.04)</td>
<td>0.14 (0.01)</td>
<td>-0.15 to -0.11</td>
<td>3.14</td>
</tr>
<tr>
<td>7</td>
<td>0.30 (0.04)</td>
<td>0.15 (0.01)</td>
<td>-0.18 to -0.14</td>
<td>4.21</td>
</tr>
</tbody>
</table>

Table 7. Differences in flight times (mean ± SD) for first seven full strides of the on-ice and dry-land sprint start in short track speed skating athletes (n=6), with certainty of the estimate shown with a confidence limit (95% CL) and a magnitude of the difference indicated by an effect size (ES).

<table>
<thead>
<tr>
<th>Step Number</th>
<th>Mean (SD) Flight Time On-Ice</th>
<th>Mean (SD) Flight Time On Land</th>
<th>95% CL</th>
<th>ES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.02 (0.02)</td>
<td>0.06 (0.02)</td>
<td>0.03 to 0.06</td>
<td>2.11</td>
</tr>
<tr>
<td>2</td>
<td>0.02 (0.02)</td>
<td>0.07 (0.01)</td>
<td>0.05 to 0.06</td>
<td>3.24</td>
</tr>
<tr>
<td>3</td>
<td>0.02 (0.01)</td>
<td>0.08 (0.02)</td>
<td>0.04 to 0.07</td>
<td>3.69</td>
</tr>
<tr>
<td>4</td>
<td>0.02 (0.01)</td>
<td>0.09 (0.01)</td>
<td>0.06 to 0.08</td>
<td>5.40</td>
</tr>
<tr>
<td>5</td>
<td>0.02 (0.02)</td>
<td>0.09 (0.01)</td>
<td>0.06 to 0.08</td>
<td>4.66</td>
</tr>
<tr>
<td>6</td>
<td>0.01 (0.01)</td>
<td>0.09 (0.01)</td>
<td>0.07 to 0.08</td>
<td>6.87</td>
</tr>
</tbody>
</table>
Figure 13. Ground contact (A) and flight (B) times (mean ± SD) for the first seven strides of the short track speed skating (STSS) (●) and dry-land sprint starts (■) (n=6).

Figure 14. A comparison of individual on-ice and dry-land 14.43 m sprint start times (s). r=0.93; p<0.001) with the equation for the line of best fit y=0.64x+0.79. Dotted lines are 95% confidence limits.
Discussion and Implications

This investigation sought to compare kinematic parameters of the elite STSS start with the dry-land sprint start including sagittal plane ROMs for the hip and knee over the initial strides, ground contact and flight times over the first seven strides, and 14.43 m start performance. We observed the intra-athlete dry-land and on-ice start performance sprint times to differ by approximately 7% (0.19 s) with on-ice slower than dry-land time, which is a larger difference than the 0.03 s error of measurement reported for electronically timed sprints of similar distances (Woolford, Polgaze et al. 2013). Accompanying slower on-ice sprint performances were longer ground contacts and shorter flight times on-ice as compared to the dry-land.

When comparing these findings to the sprint kinematic literature, we observe close equivalence in maximal and minimal hip and knee angles over the standing start push off (ground contact 1) as well as first full stride (ground contacts 2 and 3). We believe that these findings indicate the on-ice start as kinematically similar to the dry-land start thereby supporting the use of dry-land sprint start training as a potential method for improving on-ice STSS start performance.

Our kinematic findings are in agreement with the long track speed skating start literature (de Koning, de Groot et al. 1989, de Koning, Thomas et al. 1995) as evinced by similarities in hip and knee joint angles observed between the present elite cohort and the elite skaters of a previous investigation (de Koning, de Groot et al. 1989) (Table 3). Our findings are also in close agreement for all hip and knee angles during the start push off and first full stride with the exception of maximal knee extension angle during the start push off (Table 3), which appears to be greater during the long track start. Additionally, our pattern of ground contacts during the start support the previous findings of fixed point force application over the initial strides, with a gradual transition to gliding over the next several strides. Whereas the transition during long track tends to occur between the 6th and 8th stride (de Koning, de Groot et al. 1989), our findings of lengthening contact times support a transition initiating earlier at stride 5 (Figure 13).
Comparison of the current findings with the long track literature tends to establish the STSS start and pre-klapskate long track start as equivalent.

In addition to demonstrating equivalence to the long track start, the STSS start also appears to be kinematically similar to the dry-land sprint start. To perform an inferential kinematic comparison between surfaces, we conducted independent t-tests between our data and the findings of Murphy et al. (Murphy, Lockie et al. 2003) and Debaere et al. (Debaere, Delecluse et al. 2013) performed during two-point field sprints and three-point athletics sprints, respectively, with the use of a publicly available spreadsheet (GraphPad 2015). As shown in Table 4 and 5, there is no clear difference between our findings and those of the previous dry-land works for all hip and knee angles during the start push off with the exception of minimal hip angle (ES=-0.85 Large; compared to Three-Point), and no difference in first full stride with the exception of maximal hip extension (ES=0.91; Large; compared to Two-Point Slow; and ES=-1.55; Very Large; compared to Three-Point). While the sagittal plane hip and knee angles between the STSS and dry-land starts appear equivalent, differences in other kinematic parameters do exist between surfaces. The results of our intra-athlete comparison show longer ground contacts (ES=3.14-5.70; very large) and shorter flight times (ES=2.11-6.87; very large) for the STSS start as compared to the dry-land start over the initial seven contacts (Table 6 and 7). These differences in ground contact times may affect the contribution of stretch shorten cycle to force production during the STSS start as stretch shorten cycle efficiency is known to decrease with increasing amortization time (Komi 2003). To the contrary, during cross-country skiing, another sport whereby an extended apparatus under the foot influences the movement kinematics and ground contact times stretch-shorten cycle is still reported to play a prominent role in driving performance (Komi and Norman 1987). Considering these potential movement similarities, it is possible stretch-shorten cycle also plays an important role in driving STSS start performance. The study also reports slower times to complete 14.43 m sprint start on-ice (2.69 ± 0.23 s) versus dry-land starts (2.50 ± 0.16 s) (Figure 14). This 7.1% discrepancy in sprint start time suggests slower sagittal plane skater velocities during the start, particularly over the initial
steps as elite 500 m speed skaters are known to display higher top speeds compared to elite 100 m sprinters (de Koning, de Groot et al. 1989).

While the establishment of STSS start parameters and general comparisons to other start modalities are important, the true value of this kinematic analysis pertains to the potential application of dry-land sprint start training as a means to develop STSS start performance. STSS start training, while indicated as important to 500 m race outcome (Maw, Proctor et al. 2006, Bullock, Martin et al. 2008, Haug, Drinkwater et al. 2015), may be overlooked at the elite level due to limits on both financial and athlete resources as the start is traditionally trained on-ice and ice time tends to be limited due to budgetary constraints. Considering, it would be of benefit to be able to effectively train the start on dry-land.

The findings of the present investigation suggests dry-land start training may potentially be an effective means of developing STSS start performance. For a training modality to exhibit a transfer of training effect to a competition variable, it must demonstrate biomechanical similarity (Zatsiorsky and Raitsin 1974, Bondarchuk 2007) with a proposed co-variation of relationship between level of congruence and performance transfer (Bondarchuk 2007, Bondarchuk 2011). The observations of the present investigation demonstrate tight equivalence in sagittal plane hip and knee kinematics to the sprint literature (Murphy, Lockie et al. 2003, Debaere, Delecluse et al. 2013) as is apparent from the almost identical maximum and minimum joint angles observed over the first three ground contacts (Table 5). While disparity exists in ground contact times and sprint times between surfaces and the STSS start is characterized by heel based ground contact (Figure 12, panel 2) as compared to forefoot contact during sprinting (Mero, Komi et al. 1992), it is our contention that the similarities in these parameters allow for a strong transfer of training effects between surfaces. While ground contacts tend to be longer during the STSS as compared to the dry-land start, the observed pattern of STSS contacts indicates a fixed-point application of force (Figure 13, Table 6 and 7), which is a defining characteristic of the dry-land sprint start. Considering application of force may be an important variable in determining transfer of
training effect, ground contacts, although different between surfaces, still support the use of dry-land sprint start training in the development of STSS performance. While sprint times and thus horizontal velocities were slower on-ice as compared to dry-land, the roughly 7% difference still supports a strong transfer of training effect between surfaces with evidence for this is purported by the relationship between weightlifting and jumping. Although peak velocity of the centre of mass velocity during vertical jumping is considerably higher than peak barbell velocity during competition snatch and clean and jerk (Roman and Shakirzyanov 1978, Roman and Treskov 1983, McBride, Triplett-Mcbride et al. 1999, Haug, Spratford et al. 2015), training with the weightlifting movements have been shown to improve vertical jump performance (Hoffman, Cooper et al. 2004, Tricoli, Lamas et al. 2005, Haug, Drinkwater et al. 2015). Considering <2.0 m•s⁻¹ barbell velocities are commonly produced during the clean (Roman and Shakirzyanov 1978, Roman and Shakirzyanov 1982) and centre of mass vertical velocities of >3.0 m•s⁻¹ produced during vertical jumping (McBride, Triplett-Mcbride et al. 1999, Haug, Spratford et al. 2015), the modest 7.1% discrepancy in sprint time observed in the current investigation should produce a large transfer of training effect between surfaces based on similarities in velocity. Additionally, although sprint times were slower on-ice as compared to dry-land, a near perfect correlation (r=0.92) was observed between surfaces (Figure 14). When sagittal plane joint kinematics, application of force, and sagittal plane skater velocity are considered in total, dry-land sprint start training appears to be a strong candidate for the development of STSS start performance. This finding is important as training the start on dry-land may improve 500 m STSS results through more optimal athlete programming. Also, considering weightlifting (Tricoli, Lamas et al. 2005, Chaouachi, Hammami et al. 2014) and resistance and jump training (Delecluse, Van Coppenolle et al. 1995, Cormie, McGuigan et al. 2010, Lockie, Murphy et al. 2012) have been demonstrated to improve dry-land sprint start performance, it is also possible that these training modalities may improve STSS start performance. This potentially provides coaches with multiple dry-land training means to supplement on-ice start training creating both greater
programming flexibility and greater variety of stimuli in which to improve performance. The importance of greater training stimuli flexibility would allow coaches to utilize their limited ice time for priority training variables applicable across race distances while still giving start training its warranted attention.
Conclusion

The STSS start demonstrates strong similarity in hip and knee joint angles, ranges of motions and the pattern of contact and flight times versus the dry-land sprint start over the first four to five strides. Of note though after the fourth stride, contact times tend to level off for the dry-land start whereas contacts tend to increase for the STSS start suggesting a transition in movement kinematics to gliding. Considering transfer of training principles, these findings suggest the first few strides of the STSS start can be effectively trained on dry-land through a sprint start intervention.
CHAPTER FIVE
Chapter 4 demonstrates strong kinematic equivalence between the STSS sprint start and the dry-land sprint start literature. Considering transfer of training principles (Zatsiorsky and Raitsin 1974, Bondarchuk 2007, Bondarchuk 2010), it seems likely that developing the dry-land sprint start will directly benefit on-ice 500 m start performance. Thus, the purpose of this investigation is to directly quantify the effects of four weeks of dry-land sprint start training on high-level STSS start performance.
The Impact Of Dry-Land Sprint Start Training On Short Track Speed Skating Start Performance

SUBMITTED- *Research Quarterly for Exercise and Sport*
Introduction

It is reported that short track speed skating (STSS) depends heavily on athlete start performance, with the 500 m event more heavily influenced than the 1000 m and 1500 m competition distances (Bullock, Martin et al. 2008, Muehlbauer and Schindler 2011). This concept was originally reported by Maw et al. (2006), who determined the start as so important in 500 m competition, that being slightly closer to the first corner block due to the geometry of the start line in relation to the first corner provides a statistical advantage during international competition. Although the start is reported to predict the final performance result, limitations on-ice time in combination with a large number of other physiological, technical, and tactical priorities also trained exclusively on-ice may only allow for sub-optimal programming of start training. Considering the importance of the start in particular for the 500 m event, it would be of benefit from a training resource allocation perspective to develop the start on dry-land.

For any dry-land training to benefit the 500 m start, there must exist a transfer of training effect between modalities. The level of transfer from training movement to competition skill may be gradual and depend on the overall equivalence between movements (Zatsiorsky and Raitsin 1974, Bondarchuk 2007, Bondarchuk 2011). Inter-movement equivalence may be multifactorial and influenced by similarities in the overall motor pattern and application of force, force-velocity parameters, and joint angles utilized (Zatsiorsky and Raitsin 1974, Bondarchuk 2007). Best scientific evidence points to a relationship between level of overall transfer and strength of relationship in each individual contributing factor (Zatsiorsky and Raitsin 1974, Bondarchuk 2007, Bondarchuk 2010). The STSS start has been demonstrated as kinematically similar to the dry-land sprint start
over the first several strides. This includes equivalence in movement pattern and force application as both movements require rearward-directed, fixed-point force application as well as similarities in the joint angles utilized (de Koning, de Groot et al. 1989, de Koning, Thomas et al. 1995). Considering the substantial kinematic overlap between the dry-land and on-ice start, it follows logically that dry-land sprint start training would be an effective modality in the development of on-ice start performance.

While theoretically dry-land sprint start training should contribute to the development of STSS start performance, no empirical evidence currently exists. Thus, the purpose of this investigation was to determine the effects of a four-week specific dry-land sprint start training intervention on STSS start performance. The results would both establish and quantify the relationship between dry-land sprint start training and on-ice start performance so that coaches and athletes may progress towards better overall allocation of available training resources through the inclusion of alternative start training modalities. Additionally, this would be the first investigation to quantify the effects of a start training intervention on on-ice start performance.

Methods

Subjects. Athletes recruited for this investigation were 5 trained (3 males and 2 females) and 4 elite male short track speed skaters between 16 and 26 y. The athletes' physical characteristics were 20.7 ± 6.7 y, 175.3 ± 6.5 cm, 70.6 ± 6.5 kg, with 4.6 ± 2.3 y (range of 1 to 7 years) training experience at study commencement. Athletes were considered trained if they competed at the national level and elite if they were a member of the national team program. All athletes provided informed consent under the approval requirements of the institution’s human research ethics committee. Furthermore, all athletes were
clearly informed that participation was not used as criteria for state or national team selections.

*Design.* This training investigation employed a single crossover design utilising a control phase followed by training intervention in highly trained skaters. The control period was four weeks duration followed by a four week intervention period; however, due to competition travel scheduling, for several athletes the control period was two weeks duration. After the control period a four week training protocol of dry-land sprint training was conducted comprising 9 electronically timed dry-land sprints with training sessions conducted twice per week. Inter- and intra-session sprint time feedback was provided on each occasion with athletes encouraged to break previous best times. Each phase of the investigation included pre- and post-testing of 14.43 m sprint times conducted both under on-ice and dry-land conditions. The dependent variables examined between control and intervention were both dry-land and on-ice sprint performance times.

*Assessment of Start Performance.* On-ice and dry-land testing sessions were conducted on separate days a minimum of 48 hrs apart. Infrared electronic timing lights (Swift Performance Equipment, Carole Park QLD, Australia) were positioned on standard prepared ice of a STSS circuit contained within a standard Olympic sized hockey rink and separately on level running surface. Timing lights were positioned perpendicular to the linear plane of motion with a distance between lights of 14.43 m. This distance represents both the mean and median distance between start line and first corner block (14.435 m) during STSS competition while within the limitations of human measurement accuracy. Each sprint was completed using a 2-point stance where athletes started in a stationary position from a line 0.30 m before the start line. Each subject performed a self-selected warm-up of at least 10 min which included 3 to 5 sub-maximal
starts. In accordance with International Skating Union rules (ISU) (ISU 2012), each skater was individually summoned to the start line with the verbal command “go to the start”. After achieving a stationary position each athlete was given the verbal command “ready”, signalling the athlete into their individual starting position. Once in position, the verbal command “go” was yelled at which point the athlete delivered a maximal skating or sprinting effort through both sets of electronic timing gates for either testing surface. On-ice, timing gates were set in the linear plane of movement; however, athletes were instructed to follow normal competition trajectories including procession around the corner post-finish-line. On dry-land, athletes were encouraged to achieve a comfortable start position similar to their on-ice position, but to conduct the test in accordance with pure dry-land sprint start mechanics. Dry-land sprints were completely linear in nature. Each athlete completed 3 maximal efforts with a minimum of 3 min rest between trials on both surfaces.

**Interventions.** Athletes performed low, equivalent volumes of on-ice standing start training over the control and intervention periods. Additionally, because the entirety of the study occurred during a single block of the pre-season and because the control period immediately preceded the intervention, training volumes, loads, and exercise selections demonstrated equivalence across the entirety of the investigation (i.e. between control and intervention periods). Training was typical for early season STSS training with primary off-ice focus of cycling (elite: 3-5 hrs/week, trained: 0-2 hrs/week), dry-land skating imitation (elite: 4-7 hrs/week, trained: 1-3 hrs/week), and resistance training (elite: 3-5 hrs/week, trained: 0-3 hrs/week) while the primary on-ice training focus was on technical drills and longer lap sets at sub-maximal intensity (elite: 6-10 hrs/week, trained: 3-5 hrs/week) (Figure 15). During the training intervention, twice per week, with a minimum of 48 hrs between sessions, athletes completed supervised dry-land
sprint start training over the same distance that they were tested. After a thorough standardized warm-up including dynamic movements of submaximal to near maximal effort identical to that used in dry-land testing, athletes performed three (3) sets of three (3) repetitions dry-land sprint starts (i.e. 9 total efforts). A minimum of 2 min rest was given between repetitions and a 3-5 min rest between sets. Electronic timing gate set-up was identical to dry-land sprint start testing including the verbal commands for starting instruction. Athletes were not provided specific technical sprint drills during the intervention. At the beginning of each training session, athletes were verbally alerted to their best previous dry-land sprint start time and encouraged to try to break that mark during the current session. Within each session, each athlete was provided with verbal feedback of the performance time for each repetition and encouraged to break their lowest intra-session time. All athletes completed 6 repetitions during the first session as an introduction to the novel maximal effort stimulus which thereafter was the minimum number of repetitions completed per training session. Athletes were encouraged to complete 9 efforts in each subsequent session however this was adjusted as guided by fatigue from the overall training load. All athletes completed the full 9 repetitions during at least 5 training sessions. To ensure each athlete was in a fresh and consistent performance state at each test, testing was scheduled on days following a light training day and athletes were asked not to participate in any extracurricular training.

Statistical Analysis. All raw data is presented as mean ± SD while to avoid the shortcomings of research analysis based in null-hypothesis significance testing, magnitude-based inferences and precision of estimation were employed (Hopkins, Marshall et al. 2009). Magnitude-based inferences on the differences in both on-ice and dry-land performance were examined by dependent t-test. Effect sizes (ES) were calculated and interpreted qualitatively as
trivial; <0.2, small; 0.2–<0.6, moderate; 0.6–<1.2, large; 1.2–<2.0, very large; >2.0 (Hopkins, Marshall et al. 2009). Effects with confidence limits overlapping the thresholds for small positive and negative effects (exceeding 0.2 of the standard deviation on both sides of the null) were defined as unclear. Clear small or larger effect sizes were defined as substantial (Liow and Hopkins 2003). Precision of estimates were indicated with 95% confidence limits, which defines the range representing the uncertainty in the true value of the (unknown) population mean.

A regression analysis (Prism 6, GraphPad Software, San Diego, CA, USA) was conducted both before and separately after the intervention period to obtain coefficient of determinations and the regression equation to predict on-ice sprint start 14.43 m performance from dry-land 14.43 m sprint start performance.

![Figure 15. Total average weekly training volume for Elite and Trained skaters over the control and intervention periods. Training during this time was divided into cycling, dry-land skating imitation, gym-based resistance training, and on-ice.](image-url)
Results

Athletes began the control period with a performance time (mean ± SD) for on-ice and dry-land sprinting of 2.72 ± 0.21 s and 2.63 ± 0.15 s respectively (Figure 16). There was no substantial change (ES: -0.05; Figure 16) for on-ice sprint start performance over the control period with a post time of 2.71 ± 0.21 s (Figure 16). A mean improvement of 2.7 % with a small effect (ES: -0.49) was observed for dry-land sprint performance over the same time period finishing with a post time of 2.56 ± 0.15 s (Figure 16 and 17).

Prior to beginning the intervention athlete’s performance time for on-ice and dry-land sprinting was 2.72 ± 0.21 s and 2.55 ± 0.14 s respectively (Figure 16). The intervention resulted in a small (ES: -0.33; Figure 17) on-ice sprint improvement of 2.6 % and a post time of 2.65 ± 0.20 s (Figure 16). The magnitude of dry-land sprint improvement was similar at 1.6 % and a post time of 2.51 ± 0.16 s which was a small effect (ES: -0.29) (Figure 16).

The relationship between dry-land and on-ice sprint start performance changed from pre- (r=0.81; p<0.0001) to post- (r=0.94; p=0.0002) intervention with a corresponding increase in slope of equation from y=1.08x-0.09 (pre-) to y=1.21x-0.38 (post-) (Figure 18).
**Figure 16.** Absolute group mean (n=9) change (solid symbol and horizontal line) with 95% Confidence Limits, and individual mean (n=3) change (open symbol) for Control on-ice (●), Control on dry-land (■), Intervention on-ice (▲), and Intervention on dry-land (♦) for absolute sprint performance.

**Figure 17.** Effect sizes and 95% CLs of pre- to post-intervention difference in 14.43 m on-ice and dry-land sprint time (s) for the control and intervention. The shaded area indicates where effect size is trivial; an effect size of <0.2 with error bars expanding >0.2 show an unclear result.
Figure 18. Data collapsed across investigation periods for the relationship between mean (n=29) dry-land and on-ice 14.43 m sprint time (s) control and pre- (○) with dashed line of best fit post- (■) intervention with solid line of best fit.

Discussion

This investigation reports that four weeks of specific supervised dry-land sprint start training in addition to minimal volumes of on-ice start training will produce a clear small (ES: -0.33; Figure 17) improvement in the STSS competition start. Considering the documented relationship between 500 m start performance and race outcome (Maw, Proctor et al. 2006, Bullock, Martin et al. 2008), our finding will have relevance to coaches looking for a novel start training stimulus or with limitations on available ice time. The finding of an average decrease in sprint time of 0.07 s (Figure 16) is considered a meaningful change such that it is greater than the reported typical error of measurement in ≤ 20 m sprinting of 0.03 s (Woolford, Polgaze et al. 2013). The
magnitude of improvements reported are important as elite 500 m race outcome is indicated to depend substantially on start performance with position at first block explaining 36% of race outcome over three seasons of World Cups and two Olympic Games (Haug, Drinkwater et al. 2015). The changes in on-ice performance following the intervention were paralleled by small (ES=-0.29, 95% CL: -0.60 to 0.03), but substantial improvements in dry-land sprint time, which is further supported by the strong relationship between-surface sprint start performance (Figure 3). Considering the biomechanical equivalence between the dry-land and on-ice STSS sprint start (de Koning, de Groot et al. 1989, de Koning, Thomas et al. 1995) and lack of on-ice improvement observed during the control period (Figure 16), the performance improvements most likely result directly from the dry-land start training. This finding supports the concept of transfer of training (Zatsiorsky and Raitsin 1974, Bondarchuk 2007), defined as performance improvement in one motor task resulting from the development of a kinetically and kinematically similar task. While previous works have demonstrated this concept in sprinting (Bondarchuk 2007), jumping (Bondarchuk 2007), throwing (Bondarchuk 2007), Olympic weightlifting (Medvedev 1989), and resistance training (Zatsiorsky and Raitsin 1974), to the authors’ knowledge this is the first investigation to report an effect between a dry-land training modality and any on-ice discipline.

Of interest is the change in relationship between surfaces of sprint performance following the training intervention (Figure 18). Such that following dry-land sprint training the strength of relationship increased (Pre: r=0.81; Post: r=0.94) indicating a stronger relationship between dry-land and on-ice sprint performance with training. We attribute this change potentially to specific technique skill improvements learned on dry-land that were able to carry over and effect on-ice performance. A strong relationship between surface sprint performance existed pre-intervention as the
general motor patterns between surfaces demonstrate equivalence. However, we propose that following dry-land training athletes were able to better identify intrinsic technical efficiencies that they were then able to transfer to on-ice performance thus cementing the stronger reported relationship.

While the intervention resulted in performance improvements, it is possible that limitations unavoidable in studying high-performance athletes blunted the magnitude of change possible with this type of intervention. It is likely increasing the length of the intervention, increasing the number of training sessions per week, increasing the number of study participants, and decreasing the remainder of the training volume could have led to larger performance gains. Additionally, the high-performance environment did not allow control for overall training volume as athletes performed more training in the experimental period (i.e. three sets of three 14.43 m dry-land sprints two times per week) than during the control. Unfortunately, the realities of the competitive environments enforced limitations on our ability to manipulate these variables. Another point of interest is the small effect (Figure 16) of the control period on dry-land sprint performance. Although no dry-land sprint start training was performed during this period, we believe it likely that the novelty of the timing system as a feedback stimulus, led to a minor performance improvement in the recorded baseline result as novel feedback stimuli have been shown to lead to positive performance improvements in other sporting disciplines (Bondarchuk 2011). It is also conceivable that the initial testing session resulted in a learning effect that carried into the follow-up testing session that was not reflected in the on-ice performance test. Despite the dry-land performance test improvement over the control period, it is still likely that on-ice improvements over the intervention can be attributed to dry-land sprint start performance training as the initial dry-land cohort start time of 2.63 ± 0.15 s appears to be
artificially high for athletes of this calibre (Chapter 4). Also, because on-ice times improved only over the intervention period, it is likely these improvements can be directly attributed to dry-land sprint start training. In hindsight it may have been beneficial to have considered including the 5 m and 10 m split times in this investigation; however, we were limited by the availability of testing apparatus that was compatible with testing on-ice. The equivalence in motor pattern between dry-land and on-ice sprint performance only over the first 6-8 strides has been reported (de Koning, de Groot et al. 1989, de Koning, Thomas et al. 1995), and it would have been useful to see these split times of the testing distance to gain further insight into where performance improvements were occurring between surfaces.

**Practical Applications**

The STSS start may be effectively trained through dry-land sprint start interventions in combination with minimal on-ice start training with performance gains in trained and elite athletes expected in as little as four weeks of training. Coaches and athletes may expect a decrease of 0.01 to 0.13 s over the first 14.43 m with similar changes in dry-land start performance. These findings allow coaches to provide athletes with a fresh start training stimulus and free-up ice time formerly dedicated to start training to other priority areas.

**Conclusions**

Trained and elite short track speed skaters can improve on-ice start performance in as little as four weeks in response to a supervised dry-land sprint start intervention. An intervention of this length may produce clear small performance improvements on-ice with parallel improvements in dry-land sprint start performance.
CHAPTER SIX
Chapters 4 and 5 demonstrate dry-land sprint start training as capable of improving STSS 500 m start performance. Considering resistance training with vertical jump training and weightlifting training have both been systematically demonstrated to benefit dry-land sprint start performance, it is likely they will also directly benefit 500 m start performance. Unfortunately, it is currently unknown if weightlifting training offers additional benefits to resistance and jump training alone. Thus, the purpose of this investigation is to compare vertical jump strategies between elite short track speed skaters and trained Olympic weightlifters; two groups of athletes both highly resistance and vertical jump trained; however, with different histories in training with the Olympic lifts.
Differences In End Range Of Motion Vertical Jump Kinetic 
And Kinematic Strategies Between Trained Weightlifters 
And Elite Short Track Speed Skaters 

IN PRESS- Journal of Strength and Conditioning Research
**Introduction**

Vertical power production is a trainable physical characteristic that is a reported performance determining variable across many sports (Stone 1993, Haff 2001) with particular relevance to maximal sprinting (McBride, Triplett-McBride et al. 2002) and jumping (Tricoli, Lamas et al. 2005). Power is the product of force and velocity, representing the ability to produce force at velocity under the limitations of cross-bridge cycling as first described by Hill (1938) in the concentric force-velocity curve. Power is relevant to movements requiring ballistic acceleration of a significant mass as it defines the ability to further accelerate the mass as increasing levels of velocity are achieved (Ohanion 1985). While power is a physical variable and often reported with peak values during scientific investigations (McBride, Triplett-McBride et al. 1999, Hoffman, Cooper et al. 2004), practically, being “powerful” is the realization of peak displacement. Peak vertical displacement is the result of vertical velocity in conjunction with the height of the centre of mass (COM) at toe off (Moir 2008, Chiu and Salem 2010). While increasing COM height at toe off will improve displacement, the practical ability to do so is confined within a limited range leaving vertical velocity at toe off as the precedent variable (Dapena and Ficklin 2007, Moir 2008). On closer examination, vertical velocity is determined by vertical impulse, which is force integrated over time of the concentric range of motion (Ohanion 1985). Thus, maximization of vertical displacement is largely dependent on maximization of vertical impulse within the physical constraints of the musculoskeletal system (van Ingen Schenau, Bobbert et al. 1987, Pandy, Zajac et al. 1990). While any increase in area under the curve will result in augmented impulse, the majority of previous works tend to quantify changes of a limited number of variables: peak force (McBride, Triplett-McBride et al. 1999, Haff, Carlock et al. 2005), rate of force development (RFD) (Häkkinen, Komi et al. 1987, Häkkinen, Pakarinen et al. 1990), and peak power (Hoffman, Cooper et al. 2004, Hawkins, Doyle et al. 2009), thus leaving changes to other areas of the force-time curve unexplored.
Acknowledging that changes in peak force, RFD, and peak power all provide insight into the relationship between impulse and vertical displacement, it is possible other factors may also influence performance outcome. Kinetic changes across the end concentric range of motion (ROM) would positively influence impulse and these have not been systematically quantified, although previous modelling work (Pandy, Zajac et al. 1990) suggests that optimal vertical jump strategies are void of lower body joint decelerations during concentric ground contact. This theoretical model is contrasted by empirical evidence as even trained jumping athletes are reported to exhibit deceleration of all lower body joints prior to toe off (Bobbert and van Ingen Schenau 1988).

Jump and resistance training (Cormie, McGuigan et al. 2010, Cormie, McGuigan et al. 2010) and separately weightlifting training (Tricoli, Lamas et al. 2005, Arabatzi, Kellis et al. 2010, Arabatzi and Kellis 2012) are known to positively affect vertical jump performance with both modalities reported to affect peak force (McBride, Triplett-Mcbride et al. 1999), RFD (Häkkinen, Komi et al. 1987, Häkkinen and Myllylä 1990), and peak power (Tricoli, Lamas et al. 2005, Cormie, McGuigan et al. 2010, Cormie, McGuigan et al. 2010). However, there is a paucity of investigations identifying changes in end ROM strategy as to our knowledge, only Arabatzi and Kellis (2012) indirectly established a relationship of changes in knee extensor co-activation strategies with power clean training. Considering this discrepancy between theory and practice, it is possible that environmental factors such as training history may influence the end ROM kinetic strategy and thus vertical impulse. Identifying between group differences in strategy would not only provide evidence for a novel mechanism by which power training functions to improve jump performance, but would also provide substantive between training modality comparison. While weightlifting and separately jump and resistance training have both been demonstrated to improve jump performance, systematic evidence identifying a superior training means is currently lacking. Therefore, the purpose of this investigation was to compare end ROM kinetic and kinematic strategies between two groups of highly trained athletes (short track speed skaters and weightlifters) and a group of
physically active participants. Considering equivalence in training history of the athlete groups (i.e. both groups were highly jump trained and highly resistance trained), but with differences in weightlifting experience, we theorised that likely differences in strategy can be attributed to adaptations fostered specifically through weightlifting. Identifying differences in end ROM jump kinetics and kinematics between groups may expose particular mechanisms by which power training improves vertical jump performance and potentially indicate weightlifting as a more effective modality of power development as compared to jump and resistance training alone.

Methods

Experimental Approach to the Problem. This study was an observational comparison of end ROM vertical jump kinetic and kinematic strategies between three groups: Elite short track speed skaters (STSS), trained weightlifters (WL), and controls (C) (Table 8). Unloaded squat jumps (SJ) and countermovement jumps (CMJ) were captured with a 15 camera motion analysis system synchronised with two in-ground force plates. End ROM kinetic and kinematic variables were analysed between groups to evaluate differences in jumping strategies.

Subjects. We sought to recruit an athlete cohort that would allow for systematic consideration of sporting background and athletic training history. Thus each subject group was identified and recruited based on their particular sporting competition background (weightlifting, short track speed skating or not competitive) and each individual’s training history for vertical power development (weightlifting, resistance and jump training, or none at all). Investigative groups were closely sex aligned between 5 national program STSS (4 men and 1 woman), 4 trained (Australian Weightlifting Federation B and C class) WL (3 men and 1 woman) and 6 physically active C individuals (4 men and 2 women). Participants’ physical characteristics (mean ± SD) of age, height, body mass, and number of years training experience are summarised in Table 1. Athletes were aged between 17 and 33 yrs at the time of the investigation. Importantly each athlete group was naïve to the other discipline of the investigation (e.g. speed skaters were naïve to weightlifting); however, both training groups were highly familiar
with bilateral jump training and resistance training while the control participants were not experienced with any form of lower body resistance training at the time of the investigation (Table 8). All participants volunteered for inclusion in the investigation and informed consent was obtained from each participant or from participant and parent or guardian if under the age of 18 yrs in accordance with both Charles Sturt University’s and the Australian Institute of Sport’s Human Research Ethics Committee approval.

**Table 8.** Athlete characteristics during vertical jump testing.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Weightlifters (n=4)</th>
<th>Speed Skaters (n=5)</th>
<th>Control (n=6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (y)</td>
<td>27.25 ± 4.6</td>
<td>19.0 ± 2.4</td>
<td>25.0 ± 2.1</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>172.7 ± 5.6</td>
<td>177.3 ± 9.8</td>
<td>177.9 ± 5.81</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>77.1 ± 4.7</td>
<td>69.0 ± 14.9</td>
<td>69.2 ± 11.2</td>
</tr>
<tr>
<td>Years of Sport Experience</td>
<td>2.3 ± 1.0</td>
<td>8.4 ± 4.4</td>
<td>-</td>
</tr>
<tr>
<td>Years of Resistance</td>
<td>5.3 ± 3.2</td>
<td>3.8 ± 1.92</td>
<td>-</td>
</tr>
</tbody>
</table>

**Procedures.** Jump testing was performed using three-dimensional marker trajectories captured with a 15-camera, VICON motion analysis system sampling at 250 Hz (Oxford Metrics Ltd, Oxford, UK). Synchronised ground reaction force (GRF) data was captured at 1000 Hz using two 600 x 900 mm Kistler force plates (Kistler Instrument, Winterthur, Switzerland). Three-dimensional kinematic data was calculated using previously validated methods (Besier, Sturnieks et al. 2003). The model (Besier, Sturnieks et al. 2003) contained seven segments and consisted of the pelvis, right and left thighs, shanks and feet. A single retro-reflective marker placed on the right and left anterior and posterior superior iliac spines defined the pelvis. Thigh and shank segments were defined by two three-marker clusters with the first cluster affixed to the lateral aspect of the thigh, aligned with the femur head and lateral femoral epicondyle. While the second cluster was affixed to the lateral aspect of the shank, aligned with the lateral femoral epicondyle and lateral malleolus. Three single retro-reflective markers positioned on the
superior-posterior aspect of the calcaneus, and first and fifth metatarsals defined the foot with inversion/eversion and foot abduction/adduction measured to assist in defining the anatomical coordinate system of the segment. Knee and ankle joint centres were defined as the midpoint between markers on the medial and lateral femoral epicondyles and medial and lateral malleoli, respectively; however, these were removed during jump trials. The hip joint centre was defined relative to the pelvis anatomical coordinate system and estimated using a regression equation (Shea, Lenhoff et al. 1997). Joint angles were determined relative to their adjoining segments. All markers were 14 mm in diameter and were secured using double-sided tape (Creative Hair Products, Melbourne, VIC, Australia) and Fixomull® (BSN Medical, Hamburg, Germany) extensible dressing. Marker trajectory data was filtered using a Woltring filter at a mean square (MSE) of 20 Hz following a residual analysis (Winter 2005) and visual inspection of the data.

All participants performed a 10 min dynamic stretching and jumping warm-up as suggested by Turki et al. (2011). The testing protocol consisted 2 sets of 3 squat jumps (SJ) followed by 3 countermovement jumps (CMJ), all with negligible external resistance. Participants paused and reset between repetitions with 3 min rest between jump conditions. During each jump repetition each participant was instructed to hold a bar of negligible mass on their shoulders to eliminate the effects of arm swing. During SJ performance, participants maintained a self-selected squat position for 3 s followed by a maximal effort vertical jump. Participants were instructed to eliminate downward (eccentric) motion once the squat position was achieved. The CMJ was performed beginning from an erect standing position with participants performing a countermovement followed immediately by a maximal effort vertical jump. Participants were allowed to self-select countermovement speed and depth; however, all jumps were instructed to be executed with the intent to create maximal jump height. Athletes were already familiarized with both jump types; however, all participants were familiarized with SJ and CMJ movement execution during the warm-up. The protocol was repeated twice with 5 min seated rest between jump conditions. Variables of interest for both SJ and CMJ were
peak vertical displacement of COM, peak concentric vertical force/kg, peak concentric vertical power/kg, peak vertical velocity, time before toe off of peak vertical velocity, decrease in velocity from peak to toe off, time before toe off of initial hip deceleration, time before toe off of initial knee deceleration, time before toe off of initial ankle deceleration, and the difference between the height of COM at toe off versus standing height.

Data analysis. Ankle, knee, and hip angles were measured in the sagittal plane. Ankle dorsiflexion, knee and hip flexion were reported as positive, joint deceleration was defined as the initial record of joint flexion moment during the final 25% of concentric ground contact. Each repetition was divided into the common phases of eccentric (CMJ only), concentric, and flight. For CMJ, eccentric phase was defined from the beginning to end of eccentric force production (i.e. negative vertical velocity of COM). Immediately following the eccentric phase, the concentric phase was defined from the beginning to end of concentric force production (i.e. positive vertical velocity of COM up to toe off). Immediately following the concentric phase, the flight phase was defined as the period void of force production (i.e. time between toe off and landing). SJ shared the common phases of concentric and flight with CMJ; however, no eccentric phase existed. Joint kinematics, joint decelerations, power, velocity, and the three components of the GRF were extracted for statistical analysis using a customised MATLAB (Mathworks Inc., Natick, MA, USA) program and analysed by absolute time. Peak vertical displacement was determined through pelvic marker reconstruction as shown by Chiu and Salem (2010) to be valid and reliable. Each variable was reported as the mean of the six repetitions.

Statistical Analyses. To avoid the shortcomings of research based in null-hypothesis significance testing, magnitude-based inferences and precision of estimation were employed (Hopkins, Marshall et al. 2009). Magnitude-based inferences on the differences in CMJ and SJ variables were compared between groups by independent t-test. Qualitative descriptors of standardized effects were assessed using these criteria: trivial <0.2, small 0.2-0.5, moderate 0.5-0.8, large >0.8 (Cohen 1988). Effects with
confidence limits overlapping the thresholds for small positive and negative
effects (exceeding 0.2 of the standard deviation on both sides of the null)
were defined as unclear. Clear small or larger effect sizes were defined as
substantial (Liow and Hopkins 2003). Precision of estimates were indicated
with 95% confidence limits (CL), which defines the range representing the
uncertainty in the true value of the (unknown) population mean.

Results

SJ and CMJ overall jump parameters. The raw standard kinetic values for
each athlete group (WL and STSS) and control (CON) are summarised in
Table 9. In the SJ, both athlete groups demonstrated moderate to large
effects (Figure 1B and 1C) for peak displacement, force/kg, power/kg, and
velocity compared to C. A large clear effect was observed for peak
concentric power/kg between WL and STSS with unclear effects for peak
displacement, force/kg, and velocity (Figure 19A). When performing CMJ,
both WL and STSS demonstrated large effects for peak displacement,
concentric power/kg, and concentric velocity compared to C with an unclear
effect observed for peak concentric force/kg (Figure 19E and 19F). Unclear
effects were shown for all parameters between WL and STSS (Figure 19D).
Table 9. Standard SJ and CMJ kinetic parameters (mean ± SD) for the Weightlifters (WL, n=4), Short Track Speed Skaters (STSS, n=5) and Control (C, n=6) groups.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Weightlifters</th>
<th>Speed Skaters</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>SJ</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak Displacement (cm)</td>
<td>48.8 ± 5.4</td>
<td>47.1 ± 5.4</td>
<td>35.7 ± 4.6</td>
</tr>
<tr>
<td>Peak force/kg (N·kg⁻¹)</td>
<td>23.8 ± 1.5</td>
<td>22.1 ± 1.4</td>
<td>20.1 ± 1.3</td>
</tr>
<tr>
<td>Peak power/kg (W·kg⁻¹)</td>
<td>60.87 ± 4.7</td>
<td>54.6 ± 2.3</td>
<td>44.0 ± 5.3</td>
</tr>
<tr>
<td>Peak velocity (m·s⁻¹)</td>
<td>3.04 ± 0.23</td>
<td>2.83 ± 0.19</td>
<td>2.45 ± 0.19</td>
</tr>
<tr>
<td>CMJ</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak Displacement (cm)</td>
<td>52.8 ± 6.3</td>
<td>49.0 ± 6.3</td>
<td>39.2 ± 4.9</td>
</tr>
<tr>
<td>Peak force/kg (N·kg⁻¹)</td>
<td>24.8 ± 2.7</td>
<td>24.5 ± 1.0</td>
<td>22.30 ± 2.6</td>
</tr>
<tr>
<td>Peak power/kg (W·kg⁻¹)</td>
<td>60.7 ± 4.8</td>
<td>56.6 ± 3.4</td>
<td>45.83 ± 6.4</td>
</tr>
<tr>
<td>Peak velocity (m·s⁻¹)</td>
<td>3.15 ± 0.23</td>
<td>2.94 ± 0.20</td>
<td>2.56 ± 0.19</td>
</tr>
</tbody>
</table>
Figure 19. Between-group effect sizes for peak displacement in cm (●), peak concentric force/ kg (■), peak concentric power/kg (▲), and peak concentric velocity in (♦) during SJ for A) WL vs ST; B) WL vs C; C) ST vs C; and during CMJ for D) WL vs ST; E) WL vs C; F) ST vs C. Error bars show 95% confidence limits of the actual effect size. The shaded area indicates where effect size is trivial; an effect size of >0.2 with error bars expanding <0.2 show an unclear result.
End Range of Motion Vertical Jump Strategy

Changes in vertical velocity. During SJ performance there was a large effect (Figure 20A and 20B) for the difference in time before toe off of peak vertical velocity for WL (8 ± 6 ms) compared to STSS (21 ± 7 ms) and C (30 ± 5 ms) while STSS demonstrated a moderate effect (Figure 20C) when compared to C (Figure 21B). WL (-0.02 ± 0.02 m s⁻¹) demonstrated a large effect (Figure 20A and 20B) for the decrease between peak and toe off vertical velocity compared to STSS (-0.07 ± 0.04 m s⁻¹) and C (-0.12 ± 0.04 m s⁻¹); however, STSS demonstrated a minimally unclear effect (Figure 20C) compared to C (Figure 22). During CMJ performance there was a large effect (Figure 20D and 20E) for the difference in time before toe off of peak vertical velocity for WL (10 ± 8 ms) compared to both STSS (22 ± 7 ms) and C (36 ± 11 ms). In addition STSS demonstrated a moderate effect (Figure 20F) when compared to C for the difference in time before toe off of peak vertical velocity (Figure 21B). WL (-0.03 ± 0.03 m s⁻¹) demonstrated an unclear effect (Figure 20D) for the decrease between peak and toe off vertical velocity compared to STSS (-0.09 ± 0.05 m s⁻¹) and a large effect (Figure 20E) compared to C (-0.13 ± 0.04 m s⁻¹) while STSS demonstrated a moderate effect (Figure 20F) compared to C (Figure 22).

Deceleration strategy. During SJ performance there was a large effect (Figure 20A and 18B) for time of initial deceleration prior to toe off of the hip for WL (21 ± 6 ms) compared to STSS (39 ± 11 ms) and C (42 ± 11 ms), yet STSS demonstrated an unclear effect (Figure 20C) compared to C (Figure 21A). The time of initial deceleration prior to toe off of the knee during SJ for WL (15 ± 4 ms) demonstrated an unclear effect (Figure 20A) compared to STSS (33 ± 21 ms) and a large effect (Figure 20B) compared to C (31 ± 7 ms) while also STSS demonstrated an unclear effect (Figure 20C) compared to C (Figure 21A). An unclear effect (Figure 20A) was observed for WL (19 ± 3 ms) in the time of initial deceleration prior to toe off for the ankle compared to STSS (23 ± 5 ms) and a large effect (Figure 20B) compared to C (30 ± 4 ms) with a similar large effect (Figure 20C) for STSS compared to C (Figure 21A). During CMJ performance there was a large effect (Figure 20D and 20E) for time of initial deceleration prior to toe off
of the hip for WL (17 ± 10 ms) compared to STSS (35 ± 11 ms) and C (39 ± 11 ms), yet STSS demonstrated an unclear effect (Figure 20F) compared to C (Figure 21C). The time of initial deceleration prior to toe off of the knee during CMJ for WL (13 ± 4 ms) demonstrated an unclear effect (Figure 20D) compared to STSS (20 ± 7 ms) and a large effect (Figure 20E) compared to C (32 ± 9 ms) also STSS demonstrated a moderate effect (Figure 20F) compared to C (Figure 21C). An unclear effect (Figure 20D) was observed for WL (19 ± 1 ms) in the time of initial deceleration prior to toe off for the ankle compared to STSS (21 ± 5 ms) and a large effect (Figure 20E) compared to C (30 ± 6 ms) with a similar large effect (Figure 20F) for STSS compared to C (Figure 21C).

*Height of COM at toe off.* During SJ performance there was an unclear effect (Figure 20A) for the difference between height of COM at toe off and standing COM height for WL (7.5 ± 1.3 cm) compared to STSS (9.0 ± 1.7 cm) and a large effect (Figure 20B) compared to C (10.3 ± 1.7 cm), yet STSS demonstrated an unclear effect (Figure 20C) compared to C (Figure 22). During CMJ performance there was an unclear effect (Figure 20D) for the difference between height of COM at toe off and standing COM height for WL (8.1 ± 1.9 cm) compared to STSS (8.4 ± 2.1 cm), and a large effect (Figure 20E) compared to C (11.0 ± 1.3 cm) with a large effect (Figure 20F) for STSS compared to C (Figure 21).
Figure 20. Between group effect sizes for peak velocity time differential to toe off (closed circle), peak velocity differential to toe off (closed square), COM height differential between standing and toe off (closed triangle), start of initial hip deceleration compared to toe off (open diamond), start of initial knee deceleration compared to toe off (open hexagon), start of initial hip deceleration compared to toe off (open triangle) during SJ for A) WL vs ST; B) WL vs C; C) ST vs C; and during CMJ for D) WL vs ST; E) WL vs C; F) ST vs C. Error bars show 95% confidence limits of the actual effect size. The shaded area indicates where effect size is trivial; error bars expanding through -0.2, 0.0 and 0.2 show an unclear result.
Figure 21. Between group differences (mean ± SD) in timing of A) initial deceleration prior to toe off of the lower body joints for SJ and B) peak velocity prior to toe off for both SJ and CMJ; and C) initial deceleration prior to toe off of the lower body joints for CMJ.

Figure 22. Between group differences (mean ± SD) in decrease in velocity between peak and toe off for SJ and CMJ.
Figure 23. Between group differences (mean ± SD) between height of COM at toe off and standing COM height for SJ and CMJ.

Discussion

The major finding of this investigation is WL tended to exhibit an end ROM kinetic and kinematic strategy closer to the optimal jump strategy (Pandy, Zajac et al. 1990) as compared to STSS in spite of these athlete groups having similar resistance and greater vertical jump training experiences. This outcome supports our theory that proficient weightlifting influences take off mechanics to improve the jumping strategy. The results of this investigation provide support for an overall relationship between training status and end ROM kinetic and kinematic strategy as both WL and STSS tended to show less change in the later stages of both SJ and CMJ movement as compared to the healthy, moderately active controls. Differences in observed strategy were manifested by the achievement of peak velocity later in the concentric ROM (Figure 20 and 21B) and by less of a decrease in vertical velocity between peak and toe off (Figure 20 and 21). Underlying these changes were discrepancies in lower body joint decelerations (Figure 20 and Figure 22A and C) with optimized end ROM kinetic and kinematic strategies corresponding with later decelerations.
Finally, considering differences in jumping strategy may represent training adaptations designed to maximize impulse and thus vertical displacement (Table 9), another major finding is the reported inverse relationship between end ROM kinetic and kinematic strategy and height of COM at toe off in comparison to standing height (Figure 20 and 22). The true novelty of our findings is that while previous investigations have shown the ability of weightlifting and separately jump training to develop power, no comparisons currently exist identifying the superiority of either training method. Considering that gaining weightlifting proficiency requires a qualified coach and potentially greater time investment for learning the lifts, we believe that this investigation is a fundamental step in the process of elucidating empirical evidence for coaches on why learning weightlifting is a worthwhile time investment. As importantly our results suggest that training with the weightlifting movements helps athletes to realise peak vertical displacement by optimising their take-off mechanics.

The findings of this investigation clearly support a relationship between training status and optimization of end ROM kinetic and kinematic strategy as untrained subjects (i.e. C) achieved peak vertical velocity earlier and exhibited larger decreases in vertical velocity between peak and toe off than the groups possessing resistance and jump training experience (i.e. STSS and WL). Further, subjects with weightlifting experience (i.e. WL) demonstrated an even closer alignment to the optimal jumping theory (Pandy, Zajac et al. 1990) as compared to subjects of similar training history, although, naïve to the Olympic-style lifts (i.e. STSS). It is likely these reported differences in jumping end ROM kinetic and kinematic strategies represent part of the underlying adaptations through which jump training modalities function to improve performance. Considering the relationship between peak displacement and vertical velocity at toe off (Moir 2008) and between vertical velocity and impulse (Ohanion 1985), it follows logically that training adaptations and in particular weightlifting function through the maximization of impulse at multiple targeted areas over the ROM. While previous works have demonstrated the ability of resistance, vertical jump, and weightlifting training to impact aspects of impulse such as peak force, RFD, and peak power (McBride, Triplett-
Mcbride et al. 1999, Tricoli, Lamas et al. 2005, Winchester, McBride et al. 2008, Cormie, McGuigan et al. 2010, this is the first investigation to indicate a direct relationship between these training methods and force production over the end ROM.

At least partially responsible for differences in end ROM kinetic and kinematic strategies between groups was the timing of lower body joint decelerations with WL decelerating all lower body joints later than C and decelerating the hip later than STSS (Figure 20, Figure 22A and C). Delayed deceleration of the lower body joints has been indicated in modelling of vertical jump performance as superior by Pandy et al. (1990) who theorize the optimal vertical jump strategy is completely void of lower body joint deceleration during concentric ground contact. While complete absence of deceleration may not be feasible due to the need to protect joint integrity (Arabatzi and Kellis 2012), our findings nonetheless support the timing of deceleration as plastic with training history and particularly long-term exposure to weightlifting capable of affecting change. Our findings are in line with Arabatzi and Kellis (2012), who determined changes in the agonist-antagonist relationship about the knee with 8 weeks of weightlifting training. We expand upon this work through observation of all three lower body joints and through the utilization of subject groups thoroughly resistance and vertical jump trained. While lower body deceleration strategy is at least partially responsible for the observed discrepancies in end ROM kinetics, between-group differences in GRF production capabilities at the relatively higher vertical velocities achieved around toe off cannot be discounted as a factor. Agonist force contribution at velocity may be related to intrinsic properties characteristic of each group such as fibre type distribution (Henneman, Somjen et al. 1965), muscle architecture (Abe, Fukashiro et al. 2001), and tendon insertion points (Harman 2008) or to further technical (Enoka 1988), muscular (Häkkinen, Pakarinen et al. 1988, Fry, Schilling et al. 2003), or neurological adaptations (Aagaard, Simonsen et al. 2002, Aagaard 2003) resulting from training history.

Regardless of the underlying adaptation mechanisms, our findings support vertical jump and resistance training experience as responsible for at least
some of the observed kinetic and kinematic differences between the trained athletes and C. These findings identify a targeted mechanism underlying the already established relationship between strength and power training and vertical jump performance (Tricoli, Lamas et al. 2005, Winchester, McBride et al. 2008, Cormie, McGuigan et al. 2010). Furthermore, considering STSS were elite level athletes with equal or greater jump and resistance training experience to the trained WL, it is likely the observed differences in jump strategy between WL and STSS can be attributed to differences in training history with the Olympic-style lifts. This is the first investigation to indicate training with the traditional weightlifting lifts as superior to resistance and jump training alone in shifting the kinetic and kinematic triple extension strategy to that reported as theoretically optimal. While the Olympic-style lifts demonstrate great kinetic and kinematic similarity to the vertical jump (Garhammer and Gregor 1992), weightlifting training may provide additional, systematically undocumented benefits to vertical jump training affecting areas of the force-time curve previously unexplored. We believe these benefits to be at least partially related to the superior kinaesthetic feedback provided by the lifts as compared with vertical jumping alone (Vorobyev 1978, Enoka 1988).

While end ROM kinetics are capable of affecting impulse and thus vertical velocity at toe off, it is not the only relevant variable as height of COM at toe off also determines displacement (Moir 2008). Thus, our findings of an inverse relationship between end ROM kinetic and kinematic strategy and height of COM at toe off in relation to standing COM height are paradoxical as those participants with the end ROM kinetics closer to optimal tended to have the lowest COM heights at toe off (Figures 18 and 21). We propose that optimal impulse strategy requires a lower relative height of COM at toe off, and the performance benefit of added impulse justifies the decreased COM height at toe off. This hypothesis is strongly supported by previous kinematic analysis of elite weightlifters (Roman and Shakirzyanov 1978, Harbili 2012) directly reporting sub-maximal plantar flexion values at toe off during the clean and snatch. Additionally, our laboratory has recently identified a trend towards submaximal plantar flexion values with long term hang power clean learning in elite athletes (Haug, Drinkwater et al. 2015).
Considering in practice the height of COM at toe off is confined within a limited range (Dapena and Ficklin 2007), the benefit to impulse may only need to be modest to justify the trade-off. While it seems possible that more efficient vertical impulse strategies may require sub-maximal COM heights at toe off, the current investigation does not provide insight into the areas of the force-time curve necessitating lower COM height at toe off. Because differences between groups were also reported for peak force and peak power, it is unclear if maximization of end ROM kinetics or GRF over other areas of the vertical jump movement requires a submaximal COM height at toe off.

In summary, our investigation indicates that differences in vertical jump performance may be related to training history as both vertical jump training and weightlifting training appear to function in part through the improvement of a previously unexplored aspect of vertical jump mechanics (i.e. end ROM kinetics and kinematics). Furthermore, our findings indicate that weightlifting training history may affect this aspect of jump performance to a greater extent than does vertical jump and resistance training alone. These findings thus have strong relevance to coaches and strength practitioners as they indicate weightlifting style training as potentially superior to jump training as a means to develop vertical power production due to the altered jumping mechanics. While training history may lead to improvements in end ROM kinetic and kinematic strategy, it may also paradoxically lead to decreased height of COM at toe off as compared to standing COM height. While lower height of COM at toe off results in lower peak displacement, this strategy may still be optimal as it may create conditions capable of greater overall vertical impulse and thus vertical velocity at toe off.

**Practical Applications**

These findings indicate athletes seeking to maximize vertical power development should consider weightlifting-style training in addition to jump and resistance training as a potentially superior means of affecting impulse and thus vertical jump performance as compared to jump and resistance training alone. Coaches evaluating the use of weightlifting movements in
the training of their athletes should be strongly encouraged to do so as we hypothesize that long-term use of weightlifting as a training modality leads to positive adaptations in the kinetic and kinematic performance strategy when jumping. Finally, these findings provide evidence that weightlifting training may be a superior power training modality as compared to vertical jump training.
CHAPTER SEVEN
Chapter 6 demonstrates a specific mechanism by which weightlifting training may influence vertical jump performance. This finding indicates training with the Olympic lifts in addition to vertical jump and resistance training may be of greater benefit to the vertical power production and thus sprint start performance capabilities of short track speed skaters than resistance and jump training alone. Despite these findings, training with the Olympic lifts can still not be advocated, as the learning investment necessary to reach a power benefit in these highly technical movements is still largely unknown, particularly in elite athlete populations. Thus, the purpose of this investigation is to quantify the learning process of the hang power clean in elite naïve short track speed skaters with a special focus on the time investment necessary to reach a power benefit.
Learning The Hang Power Clean: Kinetic, Kinematic, And Technical Changes In Four Weightlifting Naïve Athletes Over Long-Term Training

PUBLISHED - Journal of Strength and Conditioning Research
Introduction

The ability to produce concentric vertical power is a performance-determining variable in many sports and plays an important role in performance outcome. While vertical power production is enhanced through repetition of relevant competition sporting movements (Bondarchuk 2007, Bondarchuk 2010, Bondarchuk 2011), most elite training programs supplement with resistance-based modalities. Of the resistance training modalities shown to develop concentric vertical power production, the weightlifting movements are criterion within most elite environments. This is evidenced by 88% of NFL (Ebben and Blackard 2001), 100% of NHL (Ebben, Carroll et al. 2004), and 95% of NBA (Simenz, Dugan et al. 2005) strength and conditioning coaches surveyed reporting the utilization of the weightlifting movements in the training of their athletes.

The weightlifting movements are utilized in elite training environments as they have been robustly reported to correspond with high power production capabilities and to directly increase vertical power production. Garhammer (1980) reported peak power production in elite weightlifters between 1853 W to 4807 W for snatch and 2206 W to 4758 W for clean across weight-classes while Carlock et al. (2004) reported correlations between 0.90 and 0.93 associating peak power during vertical jumping and the weightlifting competition movements in national and international calibre male weightlifters. Training investigations by Tricoli et al. (2005) and Hawkins et al. (2009) utilizing subjects of unclear training histories, and Hoffman et al. (2004) using trained sub-elite athletes each reported a direct benefit of weightlifting training on vertical power production. While these works provide insight into the relationship between weightlifting training and vertical power production, there is still a paucity of literature systematically detailing these effects on naïve elite populations as well as the associated changes in movement technique.

While it is acknowledged that weightlifting training develops vertical power production, teaching these lifts may not actually be a worthwhile endeavour in the strength and conditioning setting considering the significant time involvement (Newton 1984, Duba, Kraemer et al. 2009, Duba, Kraemer et
al. 2009) necessary to reach a minimal level of proficiency and initial benefit (Roman and Shakirzyanov 1978, Vorobyev 1978, Roman and Treskov 1983, Garhammer 1989). This reported limitation may have the largest impact in elite training environments where the demands of maximizing sporting performance exceed the resources of the athlete or training environment. Since there may exist more areas of specific sporting mastery than can be effectively trained, elite level coaches may be particularly weary of investing the time and athlete resources necessary to effectively implement weightlifting training.

Even though weightlifting training has been robustly demonstrated to increase vertical power production, it cannot be deemed a worthwhile strength and conditioning training modality for elite athlete populations until the initial time investment necessary to reach a power benefit is understood. Thus, the purpose of this investigation was to establish and systematically document the learning investment necessary to benefit vertical power production during the squat jump and countermovement jump with weightlifting learning in elite athletes from a naïve state. Additionally, this investigation tracked the associated kinematic changes in weightlifting technique over the course of the learning process to document technical flaws in naïve elite athletes as well as changes with learning experience. In order to best understand the time investment interaction in the elite athlete training environment, particularly during an Olympic preparation, a single subject research design was employed.

**Methods**

*Experimental Approach to the Problem.* This investigation utilised a single subject, time-series design of four international calibre athletes naïve to weightlifting (Kinugasa, Cerin et al. 2004). Over the course of the investigation period (maximum of 169 days), athletes regularly attended two (2) hang power clean (HPC) learning sessions every 7 days in addition to their regular sport specific training. Monitoring of jump performance occurred approximately every 28 days during the first 110 days of the learning process using measurement of kinetic data from squat jumps (SJ), countermovement jumps (CMJ). Kinematic monitoring of the learning
progression occurred approximately every 28 days commencing after the 34th day of learning and continued through the learning process. HPC learning was performed as the first exercise following the warm-up during twice weekly gym sessions, and preceded by classic free-weight exercises for the lower body including back squat, front squat, lunge, step-up, and Romanian dead lift. A single low to medium level plyometric (e.g. jump rope, low lateral hops) exercise was introduced to the program on an individual basis after the 64th day from baseline; however, volumes were kept low and the exercise utilized was familiar from previous training history. All other weighted and unweighted jump exercises historically used in the training of these athletes were omitted from the program during the investigation period. All HPC learning sessions were taught directly via one-to-one instruction by the first author (holding qualifications with NSCA CSCS, USAW Level I, and 4+ years of experience instructing and programming the weightlifting movements to division 1 NCAA and Olympic level athletes). Teaching progression utilized a “part-whole” and “top down” approach as suggested in common coaching literature (Johnson 1982, Newton 1984, Duba, Kraemer et al. 2009, Duba, Kraemer et al. 2009). Briefly, each athlete began with a basic group of exercises (e.g. shrug, jump shrug) and progressed to greater complexity movements only when deemed proficient; however, earlier progressions were revisited throughout the learning period based on individual need. Initial teaching sessions for the first 14-28 days were time based with 20-30 minutes per gym session allocated to HPC learning. Then, based on individual athlete technical progression, duration-based sessions yielded to formalized training consisting of planned volumes, relative intensities, and rest periods. The number of total repetitions and rest periods per session were determined by the investigator and based primarily on the load and movement pattern utilized with earlier progressions involving bar work permitting the highest volume of repetitions and later progressions under greater loading permitting the fewest repetitions (all in a periodised manner). As athlete movement proficiency progressed with training experience, the load utilised was determined in consultation between athlete and investigator. The primary loading emphasis was a relative intensity sufficient to create a
training stimulus, but not so intense as to cause premature fatigue or
technical breakdown with subsequent repetitions.

Subjects. Athletes (n=4) were members of the Australian National Short Track Speed Skating Team and were registered members of the Australian Olympic Shadow Team with each voluntarily participating in the investigation. Each of the athletes had previous experience with free-weight resistance training consisting predominantly of multi-joint lower body strength exercises including squat variations, deadlifts, and lunge variations. However, all athletes were naïve to the weightlifting movements (i.e. snatch, clean, jerk) and their variations (e.g. clean pull). Athletes’ physical characteristics sex, age, weight, height, short track experience and resistance training experience are shown in Table 10. Athletes were between the ages of 17 and 22 yrs at the beginning of the investigation. No parameters of on-ice performance were kept during the investigation period as regular time trials were not part of training in this phase of their periodized plan and supplemental testing was not possible during an Olympic season. Informed consent was obtained from each participant or from participant and parent or guardian if under the age of 18. The Australian Institute of Sport and the Charles Sturt University Human Research Ethics Committees both approved this investigation.

Table 10. Athlete characteristics at baseline prior to beginning the HPC learning process.

<table>
<thead>
<tr>
<th></th>
<th>Sex</th>
<th>Age (Years)</th>
<th>Weight (kg)</th>
<th>Height (cm)</th>
<th>Short Track Experience (Years)</th>
<th>Gym Experience (Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Athlete A</td>
<td>M</td>
<td>19</td>
<td>63.2</td>
<td>175</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Athlete B</td>
<td>F</td>
<td>17</td>
<td>49.8</td>
<td>165</td>
<td>11</td>
<td>3</td>
</tr>
<tr>
<td>Athlete C</td>
<td>M</td>
<td>17</td>
<td>75.3</td>
<td>180</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>Athlete D</td>
<td>M</td>
<td>22</td>
<td>75.6</td>
<td>175</td>
<td>13</td>
<td>7</td>
</tr>
</tbody>
</table>

Monitoring Parameters. HPC monitoring commenced on the 35th day as the athletes were naïve and thus incapable of producing a HPC movement.
pattern at baseline (Day 0). During HPC monitoring, athletes performed 3 sets of 2-3 repetitions filmed from the sagittal plane (GoPro Hero 4, GoPro, San Mateo, USA) at 120 Hz with a minimum of 3 min rest between sets. Subject to athlete training status, testing sets employed 75% - 90% loads of an estimated 1RM. The following HPC kinematic variables were identified from each testing occasion: hip, knee, ankle joint angles at start concentric phase HPC (START); hip, knee, ankle joint angles and shin angle versus vertical at peak knee flexion of double knee bend HPC (TRANSITION); hip, knee, ankle joint angles at completion of second pull (PEAK EXT); torso angle vs horizon at the final rack position (CATCH); peak vertical displacement of right ankle as an indicator of vertical body mass displacement (ANKLE PVD); maximal horizontal displacement of barbell anterior to metatarsal-phalangeal joint (BB MAX HD); and, qualitative analysis of the concentric bar path trace.

All joint angle tracking was performed and analysed with Kinovea version 7.1 (Kinovea.org, open source); bar path tracking was performed with Dartfish TeamPro (Dartfish, Fribourg, Switzerland) and analysed with Image J software (National Institute of Health, Bethesda, USA). For a given frame, a measurement scale was set with a known distance of the weightlifting plate visible in frame. To compare changes in concentric sagittal plane bar path over time, a digital trace of the 2nd repetition’s bar path from a set utilizing a load between 75% - 85% estimated 1 RM HPC set at each time-point was determined. To determine BB MAX HD, a vertical reference line was placed at the metatarsal-phalangeal joint from the start position and peak horizontal distance between reference line and barbell trace recorded.

To provide insight into kinetic changes accompanying HPC learning process, vertical squat jump (SJ) and countermovement jump (CMJ) measurements were recorded via a linear position transducer (GymAware, Kinetic Performance, Mitchell, Australia). To examine how the HPC learning process impacted CMJ end range of motion strategy, force production at toe off, changes in the timing of peak velocity, and the decrease in velocity from peak to toe off was determined at each testing
occasion via force plate (FT 400, Fitness Technologies, Skye, Australia) sampling at 200 Hz. Vertical jump testing commenced at baseline (Day 0) and on each testing occasion, athletes first performed one set of 4 SJ and then a single set of 4 CMJ repetitions with no added resistance (all at body weight). All jumps were performed with a bar of minimal mass (0.2 kg) placed on the shoulders in a high barbell squat position. A minimal pause separated each jump repetition as each athlete returned themselves to the initial starting position and re-set to perform the next repetition with each set of SJ and CMJ separated by a minimum of 8 min. The variables monitored for both SJ and CMJ were: peak vertical power, peak vertical velocity, peak vertical displacement, difference between peak velocity and velocity at toe off, and elapsed time between peak velocity and toe off. While the athletes performed no additional resistance based power training over the course of the investigation, they did perform on-ice sprint protocols in conjunction with dry-land skating specific endurance vertical jump protocols approximately one to two times every 7 days as part of their regular training. All on-ice sprint and dry-land jump protocols had been performed in a similar manner by each athlete for a minimum of 3 years.

Statistical Analysis. HPC data is reported as mean ± SD of all within-testing session repetitions. Vertical jump data is reported as mean ± SD of all within-testing session repetitions for either SJ or CMJ. Typical error of measurement for CMJ has been reported as 0.02 m (Woolford, Polgaze et al. 2013) while the typical error of measurement across all joint angles was 1.77º and 0.016 m for distances.

Results

The mean number of sessions attended by each athlete was 26.00 ± 5.89 resulting in 494 ± 157.89 HPC repetitions completed. Each athlete missed a 20 day period of specific HPC training due to an international on-ice training camp where HPC training was deemed inconsistent with the periodized plan. However, HPC 3RM improved 60-70% for each athlete over the course of the investigation.

Learning Progression Vertical Jump Kinetic Changes
The SJ performance: At baseline (Day 0), the athletes produced 4452.78 ± 216.83 W, 2814.13 ± 445.75 W, 3957.49 ± 271.83 W, and 5772.46 ± 644.38 W peak power (Athletes A-D respectively). By the first jump testing occasion (Day 34) peak power increased 14.1-35.7% in all athletes with similar positive changes observed for peak velocity (3.4-13.4%) and peak vertical displacement (3.7-20.0%) (Figure 24). This trend continued through the third testing occasion (Athlete D: Day 64; Athletes A–C: Day 83) as all athletes demonstrated increases in peak power, velocity, and vertical displacement (Figure 24). Across all four jump testing occasions (Athlete D: 84 days; Athletes A and B: 109 days; Athlete C: 116 days), all athletes demonstrated improved peak power (14.1-35.7%;) and peak velocity (3.4-13.4%;); however, only three of four athletes exhibited an increase in peak vertical displacement (5.6-20.0%) with the fourth athlete observed no change (Figure 24).

The CMJ performance: Athletes at baseline produced 4437.57 ± 313.21 W, 3363.93 ± 231.11 W, 4589.93 ± 686.25 W, and 5773.81 ± 363.83 W peak power (Athletes A-D respectively). By the first jump testing occasion peak power increased for three of four athletes; peak velocity and peak displacement increased for two of four athletes (Figure 25). By the third testing occasion, two of four athletes demonstrated increases in peak power and peak velocity; peak displacement increased for three of four athletes (Figure 25). Across all four jump testing occasions, three of four athletes demonstrated increases in peak power and peak displacement; two of four athletes demonstrated increases in peak velocity (Figure 25).

Difference in vertical velocity between peak and toe off: Two of four athletes recorded a reduction in the difference between peak and toe off vertical velocity (Athlete A: 38.24%; Athlete B: 25.64%; Athlete C: -31.03%; Athlete D: -38.46%;) across all four jump testing occasions (Figure 26). Of the two athletes exhibiting this trend, Athlete C decreased on three of the four testing occasions (Day 0: 0.58 ± 0.07 m·s⁻¹; Day 34: 0.47 ± 0.12 m·s⁻¹; Day 83: 0.53 ± 0.07 m·s⁻¹; Day 115: 0.40 ± 0.04 m·s⁻¹) and Athlete D decreased on each occasion (Day 0: 0.52 ± 0.06 m·s⁻¹; Day 34: 0.51 ± 0.06 m·s⁻¹; Day 64: 0.48 ± 0.11 m·s⁻¹; Day 83: 0.32 ± 0.04 m·s⁻¹).
**Timing of peak velocity:** Changes in the elapsed time between peak velocity and toe off (Figure 26) indicate Athletes C and D had substantial time reductions across all four jump testing occasions (Athlete A: 17.60%; Athlete B: 8.47%; Athlete C: -17.76%; Athlete D: -23.08%). Interestingly, Athlete C demonstrated a decrease on three testing occasions (Day 0: 61 ± 4 ms, Day 34: 53 ± 8 ms; Day 83: 59 ± 9 ms; Day 115: 50 ± 4 ms) while Athlete D demonstrated a reduction on each occasion (Day 0: 52 ± 5 ms, Day 34: 50 ± 4 ms; Day 64: 48 ± 7 s; Day 83: 40 ± 0 ms).
Figure 24. Changes in SJ kinetic variables with HPC learning over the four testing occasions for Athlete A (circle), B (square), C (triangle), and D (diamond). Each data point represents the mean ± SD of four trials for each athlete.
Figure 25. Changes in CMJ kinetic variables with HPC learning over the four testing occasions for Athlete A (circle), B (square), C (triangle), and D (diamond). Each data point represents the mean ± SD of four trials for each athlete.
Figure 26. Changes in end range of motion CMJ kinetics: difference between peak and toe off velocity (filled shape); timing of peak velocity relative to toe off (open shape) with HPC learning over the four testing occasions for Athlete A (circle), B (square), C (triangle), and D (diamond). Each data point represents the mean ± SD of four trials for each athlete.
Learning Progression Kinematic Changes

The changes in kinematic variables during HPC learning for each athlete are summarised in Figures 27-31.

START: Across HPC kinematic testing (Athlete A: 129 days; Athlete B: 90 days; Athlete C: 136 days; Athlete D: 92 days) three of four athletes increased their ankle joint angle at the START position (Athlete A: 17.30%; Athlete B: 6.78%; Athlete C: -0.76%; Athlete D: 6.45%). This trend was evident by the second testing occasion with all four athletes demonstrating increase (Day: 62–77; Athlete A: 0.39%; Athlete B: 6.15%; Athlete C: 2.77%; Athlete D: 4.88%).

TRANSITION: All athletes decreased the shin angle versus perpendicular (Athlete A: -34.24%; Athlete B: -28.84%; Athlete C: -43.90%; Athlete D: -21.37%) and increased peak knee flexion (Athlete A: 4.86%; Athlete B: 7.27%; Athlete C: 17.35%; Athlete D: 2.60%) across HPC kinematic testing in the TRANSITION position. This trend was evident for both variables by the second testing occasion for all four athletes (Athlete A and B: Day 62; Athlete D: Day 64; Athlete C: Day 77). The magnitude of reduction in shin angle versus perpendicular at this time ranged between -5.69% to -13.80% across the four athletes. However only three of four athletes at the second testing occasion were observed to have increased peak knee flexion (Athlete A: -3.53%; Athlete B: 4.47%; Athlete C: 4.93%; Athlete D: 0.53%).

PEAK EXT: Three of four athletes decreased plantar flexion (Athlete A: -11.66%; Athlete B: 6.43%; Athlete C: -5.79%; Athlete D: -10.00%) during HPC learning with this trend observed in two of four athletes by the second occasion (Athlete A: -1.24%; Athlete B: 3.85%; Athlete C: -0.01%; Athlete D: 3.42%). At peak extension the decrease in plantar flexion was observed to occur in isolation of changes in other kinematic variables as no visible pattern of change was evident at the hip or knee for the involved athletes.

CATCH: All athletes reduced their torso angle at CATCH across HPC kinematic testing; however, the decrease in all athletes was not observable by the second testing occasion (Athlete A: 1.00%; Athlete B: 3.38%; Athlete C: 2.34%; Athlete D: 9.02%).
ANKLE PVD: At the initial HPC kinematic testing occasion (Day 34) the athletes exhibited a range of peak ankle vertical displacement with greatest displacement recorded by Athlete A (Day 34: 16.87 ± 1.09 cm), and the smallest initial displacement by Athlete B: (Day 34: 5.73 ± 0.76 cm). In contrast, by the completion of the formal learning process (Athlete B: Day 124; Athlete D: Day 126; Athlete A: Day 163; Athlete C: Day 170) all athletes exhibited similar peak ankle vertical displacements ranging between 6.51 ± 0.60 cm (Athlete B) and 8.49 ± 0.86 cm (Athlete D).

BB MAX HD: Three of four athletes decreased (Athlete A: 4.05%; Athlete B: -78.65%; Athlete C: -41.04%; Athlete D: -37.13%) across all four HPC kinematic testing occasions with this trend emergent by the second testing occasion (Athlete A: 1.51%; Athlete B: -12.75%; Athlete C: -27.50%; Athlete D: -20.32%).
Table 1. Changes in kinematic variables and sagittal plane bar path trace over the four testing occasions for Athlete A. Vertical reference line is drawn from right metatarsal-phalangeal joint at start position; deviation from this line in the finish position indicates the athlete has moved forward or backward during the catch phase. Data collection ceased when the bar reached peak vertical displacement following the catch. Values represent mean (SD) of six to nine trials for the individual athlete.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Days from Baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>34</td>
</tr>
<tr>
<td><strong>START</strong></td>
<td></td>
</tr>
<tr>
<td>Hip (˚)</td>
<td>104.75 (4.06)</td>
</tr>
<tr>
<td>Knee (˚)</td>
<td>143.63 (6.48)</td>
</tr>
<tr>
<td>Ankle (˚)</td>
<td>91.50 (3.78)</td>
</tr>
<tr>
<td><strong>TRANSITION</strong></td>
<td></td>
</tr>
<tr>
<td>Hip (˚)</td>
<td>120.50 (2.07)</td>
</tr>
<tr>
<td>Knee (˚)</td>
<td>116.88 (3.14)</td>
</tr>
<tr>
<td>Ankle (˚)</td>
<td>87.38 (2.50)</td>
</tr>
<tr>
<td>Shin v Perpendicular (˚)</td>
<td>30.75 (0.71)</td>
</tr>
<tr>
<td><strong>PEAK EXT</strong></td>
<td></td>
</tr>
<tr>
<td>Hip (˚)</td>
<td>179.50 (1.20)</td>
</tr>
<tr>
<td>Knee (˚)</td>
<td>176.75 (1.83)</td>
</tr>
<tr>
<td>Ankle (˚)</td>
<td>141.25 (2.55)</td>
</tr>
<tr>
<td><strong>CATCH</strong></td>
<td></td>
</tr>
<tr>
<td>Back v Horizon (˚)</td>
<td>87.13 (3.91)</td>
</tr>
</tbody>
</table>

Figure 27. Changes in kinematic variables and sagittal plane bar path trace over the four testing occasions for Athlete A. Vertical reference line is drawn from right metatarsal-phalangeal joint at start position; deviation from this line in the finish position indicates the athlete has moved forward or backward during the catch phase. Data collection ceased when the bar reached peak vertical displacement following the catch. Values represent mean (SD) of six to nine trials for the individual athlete.
<table>
<thead>
<tr>
<th>Variable</th>
<th>Days from Baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>34</td>
</tr>
<tr>
<td>START</td>
<td>Hip (°)</td>
</tr>
<tr>
<td></td>
<td>Knee (°)</td>
</tr>
<tr>
<td></td>
<td>Ankle (°)</td>
</tr>
<tr>
<td>TRANSITION</td>
<td>Hip (°)</td>
</tr>
<tr>
<td></td>
<td>Knee (°)</td>
</tr>
<tr>
<td></td>
<td>Ankle (°)</td>
</tr>
<tr>
<td></td>
<td>Shin v Perpendicular (°)</td>
</tr>
<tr>
<td>PEAK EXT</td>
<td>Hip (°)</td>
</tr>
<tr>
<td></td>
<td>Knee (°)</td>
</tr>
<tr>
<td></td>
<td>Ankle (°)</td>
</tr>
<tr>
<td>CATCH</td>
<td>Back v Horizon (°)</td>
</tr>
</tbody>
</table>

Figure 28. Changes in kinematic variables and sagittal plane bar path trace over the four testing occasions for Athlete B. Vertical reference line is drawn from right metatarsalphalangeal joint at start position; deviation from this line in the finish position indicates the athlete has moved forward or backward during the catch phase. Data collection ceased when the bar reached peak vertical displacement following the catch. Values represent mean (SD) of six to nine trials for the individual athlete.
<table>
<thead>
<tr>
<th>Variable</th>
<th>Days from Baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>34</td>
</tr>
<tr>
<td><strong>START</strong></td>
<td></td>
</tr>
<tr>
<td>Hip (°)</td>
<td>90.75 (3.41)</td>
</tr>
<tr>
<td>Knee (°)</td>
<td>141.88 (3.60)</td>
</tr>
<tr>
<td>Ankle (°)</td>
<td>99.25 (2.25)</td>
</tr>
<tr>
<td><strong>TRANSITION</strong></td>
<td></td>
</tr>
<tr>
<td>Hip (°)</td>
<td>116.13 (3.40)</td>
</tr>
<tr>
<td>Knee (°)</td>
<td>111.63 (4.44)</td>
</tr>
<tr>
<td>Ankle (°)</td>
<td>84.63 (2.72)</td>
</tr>
<tr>
<td>Shin v Perpendicular (°)</td>
<td>31.50 (2.39)</td>
</tr>
<tr>
<td><strong>PEAK EXT</strong></td>
<td></td>
</tr>
<tr>
<td>Hip (°)</td>
<td>181.50 (2.00)</td>
</tr>
<tr>
<td>Knee (°)</td>
<td>173.13 (4.32)</td>
</tr>
<tr>
<td>Ankle (°)</td>
<td>141.88 (2.10)</td>
</tr>
<tr>
<td><strong>CATCH</strong></td>
<td></td>
</tr>
<tr>
<td>Back v Horizon (°)</td>
<td>89.89 (5.58)</td>
</tr>
</tbody>
</table>

Figure 29. Changes in kinematic variables and sagittal plane bar path trace over the four testing occasions for Athlete C. Vertical reference line is drawn from right metatarsal-phalangeal joint at start position; deviation from this line in the finish position indicates the athlete has moved forward or backward during the catch phase. Data collection ceased when the bar reached peak vertical displacement following the catch. Values represent mean (SD) of six to nine trials for the individual athlete.
<table>
<thead>
<tr>
<th>Variable</th>
<th>Days from Baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>34</td>
</tr>
<tr>
<td>START</td>
<td></td>
</tr>
<tr>
<td>Hip (°)</td>
<td>106.33 (6.76)</td>
</tr>
<tr>
<td>Knee (°)</td>
<td>142.33 (4.87)</td>
</tr>
<tr>
<td>Ankle (°)</td>
<td>102.56 (2.30)</td>
</tr>
<tr>
<td>TRANSITION</td>
<td></td>
</tr>
<tr>
<td>Hip (°)</td>
<td>124.67 (4.80)</td>
</tr>
<tr>
<td>Knee (°)</td>
<td>123.78 (4.58)</td>
</tr>
<tr>
<td>Ankle (°)</td>
<td>105.89 (2.37)</td>
</tr>
<tr>
<td>Shin v Perpendicular (°)</td>
<td>25.22 (1.48)</td>
</tr>
<tr>
<td>PEAK EXT</td>
<td></td>
</tr>
<tr>
<td>Hip (°)</td>
<td>184.89 (4.96)</td>
</tr>
<tr>
<td>Knee (°)</td>
<td>174.67 (5.45)</td>
</tr>
<tr>
<td>Ankle (°)</td>
<td>151.67 (4.47)</td>
</tr>
<tr>
<td>CATCH</td>
<td></td>
</tr>
<tr>
<td>Back v Horizon (°)</td>
<td>85.50 (2.00)</td>
</tr>
</tbody>
</table>

Figure 30. Changes in kinematic variables and sagittal plane bar path trace over the four testing occasions for Athlete D. Vertical reference line is drawn from right metatarsal-phalangeal joint at start position; deviation from this line in the finish position indicates the athlete has moved forward or backward during the catch phase. Data collection ceased when the bar reached peak vertical displacement following the catch. Values represent mean (SD) of six to nine trials for the individual athlete.
Figure 31. Changes in (A) ANKLE PVD and (B) BB HD MAX for each athlete over the four testing occasions for Athlete A (circle), B (square), C (triangle), and D (diamond). Each data point represents the mean ± SD of six to nine trials for each athlete. X axis short tick marks indicate days from baseline of 62, 124 and 163.

Discussion

A key finding of this investigation is weightlifting training benefited vertical power production in all four elite athletes within the first 35 days of learning from a naïve state with continued effects for 84-116 days. This is evident from increased SJ peak power both at the second jump testing occasion (9.2%-32.6% increase) and across all four jump testing occasions (14.1%-
35.7% increase) for all four athletes (Figure 24). Accompanying changes in CMJ power production, two athletes demonstrated changes in end range of motion force application through clear trends towards better timing of peak velocity as well as a decreased velocity differential between peak and toe off (Figure 26) across all jump testing occasions. Accompanying increases in power production were changes in technique exhibited across all stages of the HPC for each athlete. While previous works have demonstrated the benefits of training with weightlifting techniques on vertical jump performance (Hoffman, Cooper et al. 2004, Tricoli, Lamas et al. 2005, Hawkins, Doyle et al. 2009), this is the first to specifically utilize an elite group of athletes and the first to report changes in vertical power production simultaneously with technical skill acquisition. Furthermore, this is the first investigation to track changes in movement kinematics under practical loading conditions and the first longitudinal investigation. In addition to improvements in vertical power production, we observed consistent kinematic (technique) changes in athletes’ performance of the HPC. A learning theme common to the four athletes was changes in kinematics suggesting barbell centre of mass shifted to a position more over the base of support and a more efficient utilization of hip extension to drive vertical power production. This is apparent from increases in ankle angle at START, smaller shin angles versus perpendicular at TRANSITION (Figure 27-30), and the minimization of BBMAX HD (Figure 31B) across all four HPC kinematic testing occasions. When considered together these adjustments provide evidence of a posterior directed shift in COP throughout the concentric phase of HPC and the possibility of a corresponding increase in utilization of the hip extensors to drive vertical barbell velocity (Fry, Smith et al. 2003). We also demonstrate a shift with increased expertise towards decreased plantar flexion at PEAK EXT (Figure 27-30). A further important finding is the shift towards minimal, but existent ANKLE PVD with HPC learning (Figure 31A). Importantly all of these technique changes were observed during HPC performance under loads of 75-90% 1RM (estimated), providing substantiative evidence under conditions experienced in practical training environments (Pistilli, Kaminsky et al. 2004, Stone, Pierce et al. 2006). We believe the
underpinnings of these shifts are multifactorial with the need to maximize impulse, limit the amount of ground reaction force directed at moving body mass, and perform a ballistic-intentioned movement all playing a role.

A major finding of this investigation is HPC learning from a naïve state yielded benefits to vertical power production within the initial four weeks learning for four elite short track speed skating athletes. This is the first investigation to our knowledge that systematically documents the timeframe to initial power benefit with weightlifting learning in elite athletes. These changes are verified through gains by all athletes in all parameters of SJ (peak power, peak velocity, peak displacement) as well as gains in CMJ peak power experienced by three of four athletes by Day 34. Although the HPC may be a more technical movement pattern than other power development modalities like plyometric and weighted jumps (Roman and Shakirzyanov 1978, Vorobyev 1978, Cormie, McGuigan et al. 2010, Cormie, McGuigan et al. 2011), it was capable of producing benefit within similar timeframes for our athletes (Cormie, McGuigan et al. 2010, Cormie, McGuigan et al. 2010). Considering the long-term demonstrated benefit of weightlifting training on vertical power production in combination with the flat learning curve reported in this investigation, we consider weightlifting training to be a worthwhile power development tool for these elite athletes.

In addition to the novel short term benefits documented, the results of our investigation support continued benefits on vertical power production with three of four athletes demonstrating gains in peak power, and peak velocity for SJ between the final two jump testing occasions. While it is possible the 125–171 day period was approaching a performance plateau, the comparatively technical nature of the weightlifting movements suggest much longer timeframes to staleness of stimulus. While all four athletes in this investigation were elite and quickly grasped the HPC movement pattern, no athlete approached the attainment of technical mastery at study completion. The notion of multi-year timeframes to exhibit mastery of the weightlifting movements is supported in the literature (Vorobyev 1978, Medvedev 1989, Baker 1991), though we would contend that mastery is not necessary to use HPC to improve vertical power production as observed by
the SJ and CMJ performance of these athletes (Figure 24 and 25). Considering HPC technical development can be partially defined as improved power production efficiency, improvement in technical parameters are likely to be associated with further power gains.

While Athletes C and D failed to demonstrate substantial changes in CMJ peak vertical displacement with HPC learning, both nonetheless demonstrated shifts in force application strategy. This is the first investigation to report direct changes in end range of motion jump kinetics with weightlifting training. Changes were evident from increases in vertical velocity at toe off relative to peak vertical velocity as well as the timing of peak vertical velocity closer to toe off with HPC learning (Figure 26). This trend is important as the performance outcome (i.e. peak displacement) is determined entirely by vertical velocity in combination with height of centre of mass at toe off (Moir 2008, Chiu and Salem 2010). Thus, the minimization of velocity loss between peak and toe off, potentially resulting from the timing of peak closer to toe off, should maximize peak vertical displacement. We hypothesise that trained weightlifters will tend to produce vertical velocity values at toe off closer to peak velocity than elite jumping athletes naïve to the Olympic lifts and, weightlifters accomplish this through deceleration of the hip and knee joints later in the range of motion however this yet to be systematically confirmed. This hypothesis is supported by modelling work reported by Pandy et al. (1990), who determined the theoretical maximization of displacement requires the complete absence of joint deceleration during ground contact as a means to maximize impulse. Strategies completely void of deceleration may not be practical, due to the need to protect joint integrity (Arabatzi and Kellis 2012); however, weightlifting training may function to improve vertical power production by delaying the timing of deceleration.

the above-knee HPC start position is characterized by a mid to rear directed centre of pressure (COP), with the shoulders “covering the bar” as viewed from the sagittal plane. Hip (Ono, Kubota et al. 1969, Vorobyev 1978, Roman and Shakirzyanov 1982) and ankle (Ono, Kubota et al. 1969, Roman and Shakirzyanov 1978, Roman and Shakirzyanov 1982) angles tend to approach a right angle, and knee angles tend to be obtuse and between 145º and 155º (Roman and Shakirzyanov 1978, Vorobyev 1978, Livanov and Falameyev 1983). All athletes in this investigation showed an intuition for the start position at baseline, which we attribute to pre-existing familiarity with the Romanian deadlift (RDL). Despite understanding the initial start position, athletes nonetheless demonstrated kinematic changes over the course of the investigation with differences about the ankle being the most consistent and notable (Figure 27-30). Increases in START ankle angle with learning were observed in athletes A, B and D, indicating a shift towards a mid to rear-based COP which is expected when compared to elite weightlifter kinematic analyses (Garhammer 1976, Roman and Shakirzyanov 1978, Vorobyev 1978, Garhammer 1984, Garhammer and Taylor 1984). An appropriate rearward shift keeps the bar in a more biomechanically efficient position as the knees navigate the bar and may allow for a more efficient utilization of hip extension over the course of the transition and second pull. Hip and knee start kinematics also showed change in athletes B, C and D but a greater variation in the pattern of change between athletes was observed (Figure 27-30). We propose this between-athlete variation occurs as each athlete moves from a basic conceptual understanding of the general HPC movement pattern to a more specialized motor pattern specific to their individual genetics. Once a general movement framework is understood, the kinaesthetic feedback provided by the hundreds of HPC reps performed affords each athlete an opportunity to understand optimal hip and knee positions for their individual joint leverages and technical style. An individual outcome as optimal is supported by the between-athlete differences reported in hip and knee joint angles within elite weightlifting populations (Roman and Shakirzyanov 1978, Vorobyev 1978, Roman and Shakirzyanov 1982) suggesting that a specific value or combination of values is not criterion.
Similar to START, best evidence suggests TRANSITION (position of maximal knee flexion) is characterized by a mid to ball of foot directed COP (Roman and Shakirzyanov 1978, Vorobyev 1978, Garhammer and Taylor 1984) and a shoulder position that continues to cover the bar, although to a lesser extent (Roman and Shakirzyanov 1978, Roman and Shakirzyanov 1982, Garhammer 1984). In comparison to START, proficient TRANSITION is marked by relatively greater hip angles and lesser knee and ankle angles (Roman and Shakirzyanov 1978, Vorobyev 1978, Roman and Shakirzyanov 1982) which is intuitive considering the repositioning of the knees to a more flexed position (Enoka 1979, Garhammer and Taylor 1984) and force developed through hip extension (Vorobyev 1978) as the barbell passes the lower thigh. It was observed that over time all athletes exhibited an increase in knee flexion during TRANSITION (Figure 27-30). Enoka et al. (1979) and later supported by Garhammer (1984), reported the knee extensors play a pivotal role in driving power production during the second pull of the clean. Thus, knee extension based power production over a greater range of motion (ROM) is an intuitive progression for novice athletes. While the results of this investigation lend support, this hypothesis must be considered in context as the knee does not work in isolation during the transition phase nor the second pull. Novice athletes may underutilize knee ROM during the second pull (Figures 25-30) due to an inability to effectively drive vertical barbell velocity through hip extension while simultaneously repositioning the knees to an optimal position. It is this balance between effective hip extension and simultaneous knee flexion that deems the transition phase of the HPC the toughest to master during weightlifting pulls (Stone, Pierce et al. 2006, Sakadjian, Panchuk et al. 2014).

The descriptive results of this study indicate improvements in transition phase mechanics as evidenced by changes in ankle and shin angles at TRANSITION with all athletes demonstrating a more vertical shin angle at TRANSITION and athletes A, B, and C concurrently showing greater ankle angles. These changes provide for a more vertical shank position and corresponding mid to ball of foot directed COP (Fry, Smith et al. 2003). This positioning allows not only a more efficient utilization of hip extension
during the transition phase (Vorobyev 1978, Cameron 1980), but also the continuous use of hip extension to drive power in combination with the knee and ankle extensors during the subsequent second pull (Roman and Shakirzyanov 1978). The purpose of the HPC transition is to produce vertical barbell velocity through hip extension while simultaneously setting the hips and knees in a position to maximize further power contribution during the subsequent second pull. The more mid-directed COP with HPC learning as well as the increased knee flexion at TRANSITION supports the concept of transition mechanics moving in a direction of greater efficiency for these four athletes.

Criterion angles for each joint at PEAK EXT have not been established and are hotly debated in both weightlifting and strength and conditioning circles with some coaches advocating full “triple extension” (Garhammer 1980, Johnson 1982, Burgener, Bielik et al. 1989, Pierce 1999, Pierce 1999) and others preferring more acute angles across some or all lower body joints (Roman and Shakirzyanov 1978, Roman and Shakirzyanov 1982, Gourgoulis, Aggeloussis et al. 2002, Harbili 2012, Ikeda, Jinji et al. 2012). While the benefits of maximizing impulse would support “triple extension” as the criterion, various analyses with elite weightlifters tends to discount the maximization of plantar flexion (Roman and Shakirzyanov 1978, Garhammer and Taylor 1984, Gourgoulis, Aggeloussis et al. 2002) in proficient HPC mechanics. The observations of this investigation clearly dispute the efficacy of “triple extension” at the ankle joint with all athletes progressing towards a tendency of sub-maximal plantar flexion at PEAK EXT despite being instructed to use maximal ankle extension during HPC execution (Figure 27-30). Although athletes A, C, and D trended towards decreased plantar flexion with HPC learning and the fourth athlete towards increased plantar flexion, all finished the investigation within a similar range of sub-maximal values (124.78 ± 2.33º–136.50 ±2.88º).

Our reported observation of submaximal plantar flexion with HPC learning in conjunction with elite weightlifter analyses (Roman and Shakirzyanov 1978, Roman and Treskov 1983, Harbili 2012) suggest sub-maximal plantar flexion as necessary to maximize the kinematic links during HPC. While
advocating ankle joint utilization over a fuller range of motion is intuitive considering the reliance of force production on impulse, this model does not consider lower-body biomechanics as a system. Thus it is possible that usage of the ankle joint over its end range of motion may come at the expense of effective hip extension. An optimal HPC strategy requires power production through hip extension (Roman and Shakirzyanov 1978, Vorobyev 1978, Roman and Treskov 1983); which may only be possible when the COP is more mid-foot directed through the transition and into the second pull. Under this strategy the COP still shifts towards the tarsals during the second pull; however, it may not permit a complete distal shift thus limiting plantar flexion.

There is a paucity of literature detailing joint specific angles at CATCH; however, technically proficient weightlifters have been reported to demonstrate more acute angles than do less proficient weightlifters (Roman and Shakirzyanov 1978, Vorobyev 1978). Proficient CATCH may be an indicator of correct sequencing and utilization of the lower body musculature over the preceding second pull with aggressive, but inefficient utilization of the hip resulting in larger CATCH angles. The naïve athletes in this investigation demonstrated proficient CATCH angles (Figure 27-30). The ability to perform a proficient CATCH in a relatively short learning period may indicate a more intuitive understanding of proficient hip mechanics and lower body sequencing over the course of the second pull. It is possible this intuition is the same trait that allows elite skaters to efficiently learn technical short track skills from a naïve state. Alternatively, it could be a learned skill exhibiting direct transfer from the jump training utilized by these athletes as the clean is known to be a vertical jump applied to a barbell (Garhammer and Gregor 1992).

ANKLE PVD as a measure of centre of mass displacement is a source of contention in weightlifting and strength and conditioning circles with some coaches advocating minimal values and others preferring continuous contact or zero displacement (Roman and Shakirzyanov 1978, Vorobyev 1978). The argument for continuous contact is to ensure true maximal time to apply vertical force and the minimization of vertical body mass displacement;
however, this coaching theory may not consider the link between maximal power production and ballistic movement patterns. The ANKLE PVD is used as an indicator of athlete vertical centre of mass displacement during HPC with technically proficient weightlifters tending to demonstrate smaller vertical ankle displacement values than less proficient weightlifters (Roman and Shakirzyanov 1978, Roman and Treskov 1983). Minimizing vertical centre of mass displacement may be an important factor in HPC efficiency as it creates longer times of contact between the lifter and the platform potentially aiding impulse (Roman and Treskov 1983), and because a greater percentage of vertical power production is directed at moving the mass of the bar as opposed to mass of the bar and the lifter (Garhammer 1993). Our observational data supports minimal, but not absent ANKLE PVD values as the criterion measure of HPC efficiency as this movement pattern provides the benefits of extended contact time, and approaching minimal body mass vertical displacement allowing the kinematic links to maximize power production through the given ROM. While 3 athletes in this investigation demonstrated a consistent trend with learning towards smaller ANKLE PVD values, the fourth athlete remained relatively the same with all athletes finishing in a similar range of small, but not absent peak vertical displacements (6.51 ± 0.60 cm to 8.24 ± 0.69 cm; Figure 31A). When gravitation towards a minimal ANKLE PVD value with HPC learning is considered in conjunction with gains in vertical jump parameters and HPC training maximums, it appears possible that a minimal, but present level of ANKLE PVD is necessary to maximize HPC efficiency via a ballistic motor pattern. Based on analyses of bench press and squat motions (Wilson, Newton et al. 1993, Newton, Kraemer et al. 1996, Clark, Bryant et al. 2008, Cormie, McGuigan et al. 2011), greater vertical power production is possible when ballistic versions of the movement are utilized (e.g. bench throw vs bench press). Thus ballistic movements via changes in neural strategies allow for agonist contribution over a greater ROM and decreased antagonist inhibition as compared to the non-ballistic counterpart (Newton, Kraemer et al. 1996, Cormie, McGuigan et al. 2011). Considering, it is likely maximal vertical power production during HPC must be associated with a pseudo-ballistic motor pattern. We propose that during performance
of HPC, the lifter aims to redirect the potential large displacements of body mass as ballistic power production into the bar; however, for the kinematic links of the body to function ballistically, a minimal level of displacement may still be necessary.

The findings of this investigation indicate a consistent trend for our elite athletes from novice towards proficient weightlifter mechanics as summarized by changes in bar path trace and BB MAX HD with HPC learning. While the athletes in this investigation demonstrated differences in HPC intuition at baseline, all exhibited common initial beginner tendencies as well as trends in technical improvement with learning. By learning completion, each athlete demonstrated a more posterior sagittal plane barbell starting position, steeper bar path traces during the transition phase, and reduced BBMAX HD compared to baseline (Figures 27–29, Figure 31B). These changes may be important as they direct the barbell centre of mass more over the base of support thus limiting torque requirements (Ohanion 1985) and because they create biomechanical positions allowing for more efficient utilization of the relevant musculature. In many regards, the sagittal barbell trace may be viewed as an indicator of kinematic movement proficiency. As all of our athletes demonstrate, with learning not only did the barbell remain closer to the base of support over the course of HPC, but the initial concentric movement of the barbell tended to be more vertically directed (i.e. steeper movement gradient initiating concentric phase). This may suggest increased utilization of hip extension to drive vertical power production over the transition phase as opposed to only knee extension in accordance with the previously discussed variables in this investigation.

In summary, training with the HPC benefited power production in these four elite short track speed skaters within the first four weeks of training, which despite the greater technical complexity attributed to HPC, is a comparable timeframe to other power training modalities. Training with the HPC also continued to benefit vertical power production, with these athletes continuing to experience gains between the final two jump testing occasions. Considering none of the athletes exhibited HPC mastery by
investigation completion, continued benefits of HPC training on power production are possible. With HPC training, 2 out of 4 athletes demonstrated changes in force application strategy over the end range of motion with both athletes achieving peak vertical velocity closer to toe off and exhibiting less decrease in velocity between peak and toe off with learning. These changes may demonstrate a mechanism by which HPC improves vertical power production. Despite different levels of intuition pertaining to HPC mechanics, all athletes demonstrated common technical inefficiencies at baseline as well as trends in HPC kinematics with learning. These inefficiencies were primarily related to execution of the transition phase and probably caused by a lack of innate programming and movement skill for proper double knee bend mechanics, although other potential factors cannot be discounted. With learning, all athletes trended towards more rearward directed COPs during the transition phase and peak double knee bend position indicating a more efficient utilization of hip extension to affect vertical barbell power production. The athletes of this investigation did not trend towards “triple extension” through the ankle with learning as all moved towards submaximal plantar flexion values. This may be attributed to a potential need to maximize vertical power production through hip extension, with the hip and ankle extensors potentially incapable of simultaneous efficient power production. Furthermore, the athletes trended towards minimal, but existent levels of peak vertical ankle displacement with training. This may be caused by the need for vertical displacement to approach zero to minimize the percentage of power production directed at moving body mass and to maximize the potential for impulse. However, a minimal displacement must exist to benefit from greater impulse and power production associated with ballistic movements. In summary, HPC learning from a naïve state was worthwhile for our elite athletes as they experienced benefits in vertical power production within the first four weeks of learning despite previous experience with other power training modalities. Furthermore, while our athletes demonstrated different levels of HPC intuition at baseline, common technical inefficiencies were noted as were movement trends over the course of learning.
Practical Applications

These findings provide substantial supporting evidence for the use of weightlifting training within the elite strength and conditioning environment. While previous works have demonstrated the benefits of weightlifting training on vertical power production, the amount of time investment necessary to reach a benefit was previously unknown. Considering these four athletes achieved substantial benefit within the first four weeks of learning, qualified coaches may consider removing the learning time investment as a deterrent from teaching the lifts. Additionally, coaches may consider recognizing the following beginner technical flaws and teaching the associated technical points to their elite athletes naïve to the lifts: 1) a centre to more rearward directed COP throughout the concentric phase allowing more effective utilization of hip extension; 2) the intention to plantar flex maximally with corresponding production of sub-maximal values also potentially indicating more effective utilization of hip extension; and 3) minimal, but existent vertical displacement of the athlete centre of mass indicating maximization of ground contact time, effective transfer of vertical power production into the barbell, and a corresponding ballistic intention.
CHAPTER EIGHT
DISCUSSION

The short track speed skating (STSS) 500 m event is strongly dependent on start performance with position at first block of first corner (i.e. entering first corner) explaining 36% of race outcome ($\tau=0.60$) during international competition (Chapter 3). The finding of Chapter 5 systematically reports that on-ice start performance can be effectively trained through dry-land sprint start interventions, which is supported by the close kinematic similarities determined between movements (Chapter 4) and the small but substantial gains reported in both on-ice and dry-land start performance following a four week supervised dry-land start training intervention. This thesis also reports (Chapter 6) the possibility that weightlifting training could, as a dry-land training means, be capable of positively affecting (STSS) start performance as trained weightlifters demonstrated more optimal vertical jump kinetics at the end range of motion (ROM) as compared to jump-trained elite short track speed skaters naïve to weightlifting. Adding further support, two of these short track athletes demonstrated clear trends towards improved end ROM jump strategy with hang-power clean (HPC) training (Chapter 7). Finally, these results support short timeframes to power benefit with weightlifting learning from a naïve state with all four athletes achieving power benefit after only four weeks. These findings not only support weightlifting as a relevant means for the development of STSS start performance, but provide evidence for weightlifting training as a superior modality to a combination of resistance and jump training.

While the international STSS community traditionally recognizes the start as a relevant factor in 500 m race outcome, the magnitude of importance was previously unknown, and most-likely underestimated as no direct investigation into the relationship between elite start performance and race outcome using a robust data set existed. These findings demonstrate start performance, defined as skater rank position entering first corner, explains 28% and 45% of elite 500 m race outcome for men and women respectively ($\tau=0.56$ and $\tau=0.67$). The high tau rank correlation reported indicates the start as a critical factor in 500 m race outcome dictating the priority of start
training a worthy consideration for elite level coaches. The findings (Chapter 3) agree with previous works of Maw et al. (2006), Muehlbauer and Schindler (2011), and Bullock et al. (2008) that start performance is an important factor during elite 500 m competition as passing is difficult. This is evident from the very large ($\tau=0.56 - \tau=0.67$ for men and women, respectively) and significant ($p<0.0001$) relationships observed between start performance and race outcome. Passing is likely difficult due to the rules of the sport (i.e. no skater contact), geometry of the track in combination with high skating velocities, and parity between competitors. These factors make the start unique in that it is the only time-point of a 500 m race where all skaters are aligned in a close to parallel position with a genuine and almost equal opportunity to establish a leading position that may be maintained over the remaining four laps of the race. Passing may be so difficult during elite 500 m competition that being marginally closer to the first block (i.e. centimetres) through a more interior grid position provides a statistical advantage (Maw, Proctor et al. 2006, Muehlbauer and Schindler 2011). Unfortunately, this investigation was unable to evaluate the current relationship between grid position and race outcome as skaters now earn interior grid position priority based on finish position and absolute race time from the previous competition round (ISU 2012). Since the faster skaters tend to hold the interior grid positions, reporting the relationship between grid position and race outcome now contains a substantial confounding variable. Previous work by Maw et al. (2006) performed on data from a time period when grid position was determined randomly, reported weak to moderately significant relationships between grid position and race outcome. Maw et al. (2006) also reported that the strength of relationship tended to increase with competition round indicating that the importance of the start tends to co-vary with the strength of the field. The findings of the current investigation agree as is apparent by the increase in strength of relationship with increasing absolute race intensity (Figure 9).

Although improvement in start performance is relevant for all 500 m skaters, prioritization of start training may still only be warranted on an individual athlete basis. For most elite 500 m short track speed skaters, the importance of the start follows logically. At the highest level skaters are
likely to possess similar top speeds and speed endurance capabilities. Considering passing is difficult (Maw, Proctor et al. 2006, Bullock, Martin et al. 2008, Muehlbauer and Schindler 2011) due to sport rules and track geometry in combination with high skating speeds, start performance may prove the determining factor or outcome “tie-breaker” as a marginally faster skater may not be capable of overtaking a competitor once behind. Elite skaters with typical 500 m characteristics may place focused start training as a high priority. Additionally, skaters with comparatively faster top-speeds and greater speed endurance capabilities as well as skaters possessing poor passing skills may also prioritize start training. On the contrary, skaters unable to produce or maintain elite level top speeds, skaters already capable of producing fast starts, and skaters particularly skilled at passing may benefit less from focused start training.

Although the data clearly indicate the importance of start performance in international 500 m race outcome, start training must still find a niche within overall athlete programming as the current STSS training landscape requires the majority of skaters to train and compete in three individual events in addition to a relay event. Although the start is unequivocally shown to be relevant to 500 m performance, the 500 m only represents one quarter of the total competition for most elite skaters. Therefore, prioritization of start training must be weighed against all other training variables, including those relevant across all four distances. Further complicating matters, the start has traditionally been trained exclusively on-ice, and therefore must compete for allocation within a subset of priority training variables as opposed to the general resource allocation. While it would have also been relevant to explore the relationship between start performance and race outcome at the club and national level; limited skater numbers and organised competitions combined with the lack of formalised searchable databases of results in Australia unfortunately deemed such exploration unfeasible.

Having established the importance of the start in 500 m race outcome, it was then necessary to further the understanding of kinematic similarities between dry-land and on-ice STSS starting. These findings build upon the
previous works of de Koning et al. (1989) and de Koning et al. (1995) further cementing the kinematic link between dry-land and on-ice sprint starting. While these works provide kinematic comparison between pre-klaskate long-track speed skaters and the dry-land sprint literature, this work is the first to directly examine short track speed skaters. These findings demonstrate close equivalence in hip and knee joint sagittal plane kinematics over the start push off and first full stride as compared to the dry-land sprint literature (Murphy, Lockie et al. 2003, Debaere, Delecluse et al. 2013) (Chapter 4). Additionally, while these findings demonstrate longer ground contacts and shorter flight times on-ice as compared to dry-land, the fixed point force application apparent over the initial strides is equivalent between surfaces. Unfortunately, only angular kinematics of the right leg were recorded as filming from the centre of the rink with a wired set-up was not possible. Nonetheless, with consideration to transfer of training principles (Zatsiorsky and Raitsin 1974, Bondarchuk 2007, Bondarchuk 2011), these findings indicate the dry-land sprint start as a relevant training tool for the development of STSS start performance.

Considering kinematic similarities between sprint starts on both surfaces and expected transfer of training effects, the next goal was to directly quantify the benefits of dry-land sprint start training on 500 m start performance (Chapter 5). As hypothesized, four weeks of 14.43 m dry-land sprint start training led to a small but substantial decrease (ES: -0.33) in time to first corner entrance in trained and elite level short track speed skaters. Not surprising, these changes were paralleled by similar substantial decreases in dry-land sprint time (ES: -0.29) demonstrating a strong transfer of training effect (Zatsiorsky and Raitsin 1974, Thorstensson, Karlsson et al. 1976, Bondarchuk 2007) between surfaces.

A mean improvement of 0.07 s over an approximately 2.5-2.8 sec stretch creates a substantial competitive advantage during elite 500 m racing for two reasons. Firstly, the strong parity in current international STSS competition dictates that any slight advantage a skater can possess over the competition is likely to result in tangible changes in race results (Haug, Drinkwater et al. 2015) (Chapter 3). STSS races are often won by
hundredths of a second (ISU 2012); thus, improvements of similar magnitudes are likely to influence results. Secondly, because skaters spend the majority of a race skating in series and the first delineation to in-series skating tends to occur at the first corner, being ahead of an opponent by even the slightest of margins entering the first corner produces the additional bonus of yielding a full body-length lead exiting the first corner. Besides providing the obvious benefit of the increased lead distance (i.e. full body-length versus centimetres), the skater now holds the important leading position, which is of paramount performance as passing during 500 m racing is known to be difficult (Maw, Proctor et al. 2006, Bullock, Martin et al. 2008, Haug, Drinkwater et al. 2015) (Chapter 3).

The implications of these findings are substantial for multiple reasons. Firstly, being able to effectively train the start on dry-land with a close between-surface relationship allows coaches to remove start training from the sub-set of areas capable of being trained exclusively on-ice. For training environments with limited ice time, this allows for a more efficient allocation of training resources and thus more effective athlete programming. A further benefit is the novelty to the athlete of the dry-land stimulus as it is possible training the start on dry-land and on-ice will lead to greater gains than training on-ice alone (Bondarchuk 2011). Previous works identifying adaptation processes in response to neurological training stimuli have suggested the long-term performance benefit of training with similar, but slightly varying modalities (Bondarchuk 2007, Bondarchuk 2011, Bondarchuk 2012). This may be particularly relevant for athletes of advanced training age who have exhausted a large percentage of their genetic adaptation window training solely with on-ice sprint starts. It is also possible that dry-land start training leads to superior musculotendinous and neurological adaptations brought about by the interaction between foot and dry-land training surface. Previous works investigating differences in running kinematics between surfaces of varying coefficients of friction (e.g. sand versus wood floor) observed that softer surfaces require greater energy consumption to maintain a given running pace (Pinnington, Lloyd et al. 2005, Girard, Racinais et al. 2011). The authors attributed the difference in efficiency at least in part to a less effective utilization of stored elastic
energy via stretch shorten cycle during softer surface running. While ice is classified as a hard surface, it is possible that interactions between the boot, blade, and ice during the start create an attenuated stretch shorten cycle response relative to dry-land sprint starting. Considering plyometric training has been shown to benefit power production to a greater extent on comparatively harder surfaces (Impellizzeri, Rampinini et al. 2008), it is possible that dry-land start training may produce novel gains in STSS start performance through a stretch shorten cycle mediated transfer of training effect. These gains may be neurological in nature and related to changes in reflex size (Komi 2003, Thompson, Chen et al. 2013) or may be musculotendinous in nature (Lindstedt, Reich et al. 2002) as the greater peak eccentric forces potentially experienced during dry-land sprinting may result in greater adaptations to the series elastic component and architecture of the relevant muscle. Considering these potential changes it would have been beneficial to also track hypothetical changes in both triceps surae Hoffmann-reflex and tendon structure over the course of the investigation; however, the investigated population (i.e. high level athletes) dictated these measures prohibitive.

While the relationship between dry-land sprint start training and on-ice start performance provides direct training implications, it also provides novel scientific support for further transfer of training between modalities known to improve dry-land sprint start performance and the short track start such as resistance with vertical jump training (Baker and Nance 1999, Cormie, McGuigan et al. 2010) and weightlifting training (Tricoli, Lamas et al. 2005, Hawkins, Doyle et al. 2009). Unfortunately, direct testing of STSS and dry land sprint start testing were not possible with these elite athletes during an Olympic year; nonetheless, the previously established relationship between vertical power production and sprint performance allows the possibility that resistance and power training modalities may improve STSS performance. The findings indicate that resistance and power training modalities may improve vertical power production through more optimal end ROM force application strategies as evinced by smaller decreases in vertical velocity from peak to toe off (Figure 21) (Chapter 6). This builds upon previous works identifying the ability of resistance training to influence specific
portions of the concentric force-time curve. While previous works investigated peak force (McBride, Triplett-Mcbride et al. 1999), peak power (McBride, Triplett-Mcbride et al. 1999, Hawkins, Doyle et al. 2009), and rate of force development (Häkkinen and Myllylä 1990, Winchester, McBride et al. 2008), this investigation was the first to directly support changes in end ROM strategy. The end ROM is important in determining jump performance as it is capable of affecting vertical impulse, and impulse is one of the two factors (the other being height of COM at toe off) that determine jump performance (Moir 2008). Since it is possible that changes in end ROM impulse are independent of earlier movement force production (e.g. peak force), kinetic improvements at the end ROM may offer an additional opportunity to improve performance. This opportunity is particularly relevant for athlete’s asymptote to their genetic limit at force production over other points of the force-time curve. Improvements in vertical jump performance resulting from changes in end ROM kinetics may also improve sprint start performances such as the STSS start as the dry-land start is known to co-vary with jump performance (Baker and Nance 1999, Requena, Garcia et al. 2011).

Additionally, while previous works investigating force production during jumping served primarily to identify areas of change, our investigation provides a specific mechanism (i.e. lower body deceleration strategy) by which adaptation occurs. The reported (Chapter 6) trend towards later deceleration of the hip, knee, and ankle joints approaching toe off in resistance and jump trained athletes as compared to healthy controls with large, clear differences noted across all three joints between weightlifting trained athletes and controls. Considering the relationship between vertical impulse, jump performance (Moir 2008), and sprint start performance (Baker and Nance 1999, Cormie, McGuigan et al. 2010), this finding demonstrates a precise biomechanical pathway by which resistance training may improve the STSS start.

Although the reported findings indicate resistance and jump training as capable of affecting end range of motion vertical jump force application and thus performance, training solely with these modalities may be of less
benefit to the STSS start than additionally training with the weightlifting movements. Although the speed skaters in our investigation were elite with greater jump training (WL: 2.3 ± 1.0; STSS: 8.4 ± 4.4 y) and similar overall resistance training experience as compared to the trained weightlifters (WL: 5.3 ± 3.2; STSS: 3.8 ± 1.92 y), the weightlifters demonstrated an advanced optimal end ROM vertical jump strategy. This is the first investigation to indicate an additional benefit of weightlifting training as compared to training with vertical jump and resistance training alone. Furthermore, of the four athletes to undergo HPC learning from a naïve state, two demonstrated steady changes towards improved adaptation of end ROM vertical jump strategy with training. As evident from changes in both the timing of peak velocity prior to toe off, and the smaller decrease in vertical velocity between peak and toe off. Considering differences in strategies between groups and the direct demonstration of weightlifting training to affect end ROM kinetic strategy, it seems plausible that the use of the weightlifting movements will benefit STSS start performance. These novel findings, are indirectly explained by Arabatzi and Kellis (2012) who reported changes in knee extensor co-activation strategy after 12 weeks of training with the power clean. It is proposed the decreased antagonist contribution reported by Arabatzi and Kellis (2012), is an underlying mechanism behind the observed later deceleration strategy of weightlifters in our investigation and the changes in end ROM kinetic strategy reported for two STSS athletes during HPC learning.

While a shift in deceleration strategy is a likely control mechanism underlying changes in end ROM jump kinetics with training, there are also potential physiological explanations that are not mutually exclusive. It is plausible that other neurological and peripheral muscular adaptations also enhanced impulse over this portion of the force-time curve. Neurophysiological adaptations may include more efficient inter-muscular coordination of the lower body (i.e. improved jump technique) brought on by both jump and weightlifting training, or from a subtle shift in the activated muscle’s length tension capabilities and muscle’s architectural shifts (Cormie, McGuigan et al. 2011) improving force production at the velocities achieved approaching toe off and ankle joint position. These
potential adaptations could occur in combination with greater central drive, manifesting as a combination of additional motor unit recruitment (Henneman, Somjen et al. 1965, Duchateau and Hainaut 2003) or increased firing rate of active motor units (van Cutsem, Duchateau et al. 1998). These adaptations may be complimented by peripheral muscular adaptations such as hypertrophy of high threshold type II motor units (Thorstensson 1976) which would be required to produce further contributory force at the velocities achieved approaching toe off.

While weightlifting may share common adaptation mechanisms with resistance and vertical jump training modalities (Chiu and Schilling 2005, Cormie, McGuigan et al. 2011), its true value as a synergist training means may lay in its novel and superior ability to provide kinaesthetic motor control feedback (Enoka 1988). While performance of the vertical jump does provide direct technical skill feedback, it is possible that weightlifting provides superior feedback as it pertains to jump movement optimization, or at least novel supplemental feedback. While more evidence establishing this direct connection is necessary, similarities in biomechanics (Garhammer and Gregor 1992) and force-velocity profiles (Chapter 6) (Roman and Shakirzyanov 1978, Bondarchuk 2007) between movements in combination with these findings of more optimal end ROM vertical jump strategies in weightlifting trained athletes does provide initial support.

Despite these benefits specific to weightlifting, training with these lifts cannot as yet be considered optimal for elite athletes nor for the improvement of STSS start performance as the learning investment necessary to reach power benefit has not yet been quantified. While the case study approach presented in Chapter 7 does not permit result extrapolation to entire elite athlete populations, it nonetheless provides strong supporting evidence as the four athletes investigated achieved power benefit within the first four weeks of training from a naïve state (SJ: 14.1 - 35.7%; CMJ: -2.91 - 20.79% increase). This builds upon previous works (Tricoli, Lamas et al. 2005, Hawkins, Doyle et al. 2009) identifying relatively short timeframes to power benefit in untrained and recreationally trained college aged males. Short timeframes to power benefit may be
particularly important for elite short track speed skaters, as the technical nature of the sport and lack of event specialization dictate a premium on training resources.

While the elite athletes in this investigation demonstrated individual variations in HPC styles as well as technical flaws, it is interesting to note the common movement inefficiencies at baseline as well as similarities in technical trends with HPC learning. In contrast to other investigations, the reported changes in HPC technique were consistently seen under real training loads and not under artificially light testing scenarios. All athletes tended to achieve more rearward centre of pressures over the course of ground contact as evinced by increases in ankle angles at the start and increases in shin angles versus perpendicular at the transition phase greater than the typical error of measurement. When combined, these positions allow the knees to navigate the bar with greater efficiency (Roman and Shakirzyanov 1978, Enoka 1979) and allows greater utilization of the hip extensors to drive barbell velocity over the concentric ROM (Roman and Shakirzyanov 1978, Vorobyev 1978). While it is possible this common technical inefficiency in a naïve state resulted from a lack of familiarity with double knee bend during HPC performance, athlete populations have been demonstrated to intuitively exhibit a double knee bend strategy during vertical jumping (Garhammer 1989, Garhammer and Gregor 1992). Furthermore, ground reaction force data (unreported) suggests double knee bend kinematics occurring in all four athletes in the current investigation. It is also possible that training tendencies common to short track speed skaters created the common inefficient movement kinematics. While anecdotal support for this explanation relies on the situation that three of the four athletes trained for at least five years under the same coach, it is noted that speed skating kinematics (van Ingen Schenau, de Boer et al. 1987) do not tend to produce the forefoot dominant positions exhibited by these athletes. An alternative hypothesis is the jump motor pattern potentially innate to humans or else learned through activities of daily living may tend to produce inefficient quad dominant mechanics. While this hypothesis requires further exploration, previous studies evaluating untrained jump landing mechanics (Coleman, Adrian et al. 1984, Griffin, Agel et al. 2000,
McNair, Prapavessis et al. 2000), the HPC mechanics exhibited by our naïve athletes, and anecdotal evidence during classic gym exercises such as squat and lunge all suggest forward centre of pressures and knee dominant motor patterns in untrained individuals. It is possible that although these kinematics produce sub-optimal performance, they tend to foster positions that lessen the emphasis on the hip thus protecting back health. It is also possible that motor habits formed during activities of daily living or specific strength deficiencies exhibit transfer to jump type motor patterns fostering the suboptimal motor patterns potentially witnessed.

While the weightlifting movements and related vertical jump counterparts represent a distinct set of complex motor skills, the underlying learning process and perhaps time frames to mastery are most likely similar to other complex technical skills (Anderson 1987, Gladwell 2008). Unfortunately, there is a dearth of scientific literature on timeframes to mastery of other complex sporting tasks. While counterintuitive, this may not be surprising considering this investigation is the first long-term scientific inquiry investigating the learning process underlying HPC learning, and one of the first learning investigations of any length to report outcomes from practical loading conditions. Despite this dearth of literature, weightlifting variations are potentially used in the strength and conditioning setting as a means to confer technical transfer to other sporting movements that while distinct, require vertical power production or similar movement kinematics and thus may have an underlying motor connection with the weightlifting movements. Considering this technical connection and perhaps common motor root, it is likely that while other complex motor skills are distinct, they also share some similarities and potentially similar timeframes to motor mastery. Thus, in consideration of the body of literature (Chapter 5) (Tricoli, Lamas et al. 2005, Chaouachi, Hammami et al. 2014) and transfer of training principles (Zatsiorsky and Raitsin 1974, Bondarchuk 2007, Bondarchuk 2011), it is possible that weightlifting training benefits both the dry-land and on-ice sprint start in part due to improved kinaesthetic awareness of biomechanically efficient positions capable of maximizing impulse over each stride.
CHAPTER NINE
CONCLUSIONS

This work systematically quantifies start performance as a major performance determining variable in elite 500 m STSS for both men and women (Chapter 3). This relationship is most likely attributed to similarities in top speed and speed endurance capabilities of elite skaters in combination with the difficulty associated with passing during international 500 m racing.

The importance of start performance highlights the relevance of investigating methods of improving start performance. Chapter 5 demonstrates that dry-land sprint start training is capable of improving on-ice start performance in high-level skaters. This is evident from the reported kinematic similarities between movements and through direct improvements in on-ice start performance following a training intervention. High level skaters may expect small, but substantial improvements in as little as four weeks of supplemental dry-land start training. These findings are relevant as being able to train the start on dry-land frees ice time to be allocated to other priority training areas and provides a novel start-training stimulus. These findings also establish transfer of training as possible from dry-land to on-ice indicating other dry-land modalities known to develop the sprint start as possible to also improve on-ice start performance.

For the further development of STSS start performance, additional training with weightlifting may be superior to resistance and jump training alone. This is evident from more optimal end ROM kinetic strategies exhibited by weightlifters as compared to short track speed skaters. Greater optimization persists from less decrease in vertical velocity between peak and toe off attributed at least in part to later deceleration of the lower body joints, particularly the hip joint. Considering weightlifting is known to improve sprint start performance, these findings suggest a benefit of weightlifting training that may apply to on-ice start performance.

This work reports supporting evidence of short time frames to power benefit with weightlifting training in elite naïve athletes. The four athletes in this investigation demonstrated improvements in jump performance as well as
all other tracked kinetic variables within the first four weeks of learning. Despite evidence for the ability of weightlifting to improve start performance, training with the lifts still cannot be scientifically advocated as the single case series subject design prevents extrapolation of the findings to entire athlete populations. Nonetheless, these findings provide strong support for equivalent, if not shorter timeframes of learning as compared to other gym-based power development modalities.

Despite idiosyncrasies, the four athletes investigated demonstrated common technical flaws from a naïve state as well as common kinematic trends with HPC learning. Over 4-6 months athletes exhibited more rearward-based centre of pressures over the entire movement allowing more efficient bar positions and greater utilization of the hip joint to drive vertical barbell velocity. Accompanying these changes were trends of peak vertical ankle displacement towards minimal, but existent values indicating a greater percentage of power allocated to moving the barbell as opposed to body mass with learning.

This thesis demonstrates the value of the start in STSS performance, with investigations suggesting that both dry-land sprinting and the HPC have the potential to improve STSS starting. Furthermore, it is demonstrated an actual improvement in STSS start performance after four weeks of dry-land sprint start training.
PRACTICAL APPLICATIONS

The following practical applications emanate from this thesis:

- Start performance is a major predictor variable in international 500 m STSS racing explaining 28% and 45% of race outcome for men and women, respectively.

- Considering the impact of start performance on 500 m race outcome, elite training environments may consider prioritizing start training to a greater degree for some individuals. Target individuals may include athletes with mean or better top speed and speed endurance capabilities, poor start performance characteristics, or poor passing characteristics. Athletes positioned to benefit less may possess poor top speed and speed endurance capabilities, excellent start performance characteristics, and excellent passing characteristics.

- The STSS start can effectively be trained through dry-land sprint start interventions. Highly trained athletes may expect -0.13 to -0.01 s improvements in four weeks of supplemental training with 9 timed 14.43 m efforts performed two times per week.

- The ability to effectively develop the start through dry-land sprinting provides training environments with limits on-ice time more resources allocable to other ice-specific training priorities as well as novel means by which to develop the start.

- Other modalities known to develop the dry-land sprint start such as resistance based power training modalities may also influence on-ice start performance.

- Resistance and power training may improve end ROM jump kinetics and thus vertical jump performance through delays in lower body joint deceleration during ground contact. This is evident from the more optimal strategies of resistance and vertical jump trained and weightlifting trained athletes as compared to untrained controls.
• Training with the weightlifting may be superior in the development of power and on-ice start performance as compared to resistance and vertical jump training alone as trained weightlifters demonstrated more optimal end ROM jump kinetics as compared to elite short track speed skaters with similar or more resistance and jump training experience.

• Elite athletes naïve to weightlifting training may achieve benefits to power production within the first four weeks of HPC learning. Further group-based research is necessary for systematic quantification of learning timeframes.

• Naïve athletes may demonstrate a common tendency of forward centre of pressures and over-reliance on knee extension to drive power production during hang power clean performance. With learning, athletes may demonstrate rearward shifts in centre of pressures throughout the concentric ROM allowing for more efficient barbell positions and greater utilization of the hip to drive vertical barbell velocity.

• Optimal power clean performance may utilize limited plantar flexion as the biomechanical positions necessary for proper utilization of the hip to drive barbell velocity may require more mid-based centres of pressure that prevent full extension of the ankle as toe off is reached.

• Optimal power clean performance may require minimal but existent displacement of body mass following toe off arising from the need to maximize ground contact time, but still produce a quasi-ballistic motion with limited joint deceleration.
FUTURE DIRECTIONS

Considering this thesis is one of only a handful of works to investigate the STSS start, and the first to utilise a training intervention, more scientific exploration into optimisation of 500 m start performance is still required. The immediate need is direct quantification of on-ice sprint start training on 500 m start performance in elite athlete populations as training with the competition movement is usually an effective and potentially necessary developmental means (Zatsiorsky and Raitsin 1974, Bondarchuk 2007, Bondarchuk 2010). The next relevant step will be to directly quantify the relationship between resistance-based power development modalities known to improve sprint start performance such as jump and weightlifting training and the STSS start. The next step will be investigation into the effects of resisted and assisted sprint training, means hypothesised to influence dryland starting (Myer, Ford et al. 2007, Alcaraz, Palao et al. 2008, Clark, Stearne et al. 2010, Paulson and Braun 2011), on start performance. Once these relationships have been systematically quantified, attention should turn to comparative research aimed at identifying the optimal start development modality or combination of modalities. In addition to the evaluation of modalities, understanding the effects of manipulation of the acute program variables of these modalities on start performance will also be relevant. Thus, varying the distance of sprint interventions, number of repetitions, and number of workouts per week may all influence the effect of these training modalities.

This thesis is also the first work to directly investigate optimisation of end ROM vertical jump kinetics with different training modalities. Although this work demonstrates greater optimisation with weightlifting training as compared to only jump and resistance training experience, the data also demonstrates changes in optimisation with HPC training in two elite athletes, while further systematic investigation is necessary to quantify the effects of gym-based power training on end ROM jump strategy. Furthermore, while this work shows discrepancies in the difference between peak and toe off velocities between groups as well as the ability of weightlifting training to change these kinetics, the effects of gym-based
power training on the entire force time curve (i.e. impulse) is currently unknown. While previous works have looked at other specific areas of impulse (i.e. rate of force development, peak force, peak power), no works have looked at changes in the curve profile. Considering evidence of double knee bend mechanics in vertical jumping (Garhammer and Gregor 1992) and the ability of weightlifting training to improve double knee bend mechanics (Roman and Shakirzyanov 1978, Vorobyev 1978), it is possible training with the lifts creates greater impulse through increased efficiency during this portion of the jump movements. Of further interest are the potential implications of these specific adaptations on overall elite STSS performance.

Finally, while this thesis is the first to identify the potential superiority of weightlifting as compared to resistance and jump training alone in elite athletes, further systematic comparisons between these modalities are still necessary. These investigations should focus on differences in jump, sprint, and skating performance benefits between modalities with additional inquiry into differences in areas of change (e.g. rate of force development, peak power, etc.). Furthermore, because a superior modality must also consider time to benefit as well as length of benefit, investigations comparing learning timeframes as well as both short and long term comparative benefits should be undertaken.
REFERENCES


