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The Bobsled Push Start: Influence on Race Outcome and Push Athlete Talent Identification and Monitoring

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The Bobsled Push Start: Influence on Race Outcome and Push Athlete Talent Identification and Monitoring

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by

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ABSTRACT

The Bobsled Push Start: Influence on Race Outcome and Push Athlete

Talent Identification and Monitoring

by

Alexander Pierce Harrison

Bobsled is an Olympic sport that has progressed from rudimentary in the 1800's to highly technological replete with biomechanical analyses and investment in engineering from the world's top engineers. Little to no investigation has been carried out on all the tracks and the interrelationship between various measures of starts and sled-travel down-track. Further, little quality research has been produced in the athletic characteristics required for high-level competition in bobsled.

The present manuscript investigates the reliability of, and interrelationship between, start time, start velocity, split times, and finish times in World Cup 2- and 4-man bobsled competition. A strong relationship between the three variables is found, but further research is needed to elucidate the actual effects of the push start on the sled's travel down-track because of several confounding variables.

The present manuscript also investigates the tests commonly performed by the USA Bobsled and Skeleton federation as a means of talent identification and athlete monitoring. Strength and power tests may have more validity for discriminating between higher-level push athletes, so long as a sufficient threshold of running speed is present. Speed tests only discriminate well

between lower level push athletes. Recommendations are made for modifying the current testing battery in such a way as to better identify talent and better monitor traveling athletes and informing coaching decisions about athlete preparedness for fast bobsled push starts.

DEDICATION

This manuscript is dedicated to my family. Without your frequent actions that so beautifully displayed unconditional love throughout my youth, I truly would not have accomplished half of what I have, or be who I am today. This dissertation is one small manifestation of the empowerment that unconditional love can foster.

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CHAPTER 1

INTRODUCTION

Nearly 120 years ago the first formal bobsled organization became the roots of what is now a technologically advanced winter Olympic sport (Federation, 2016b). The sport of bobsled requires a team of 2 or 4 athletes to overcome the inertia of the sled through a running start, a coordinated jump into the sled, and fine-tuned driving skills, followed by the braking action performed by the brakeman after the finish line (Federation, 2016c). Bobsled athletes are separated into two distinct classifications: drivers and push athletes, although the drivers are also required to push the sled at the start for maximum performance (Federation, 2016c).

One of the sports to be included in the first winter Olympics in Chamonix, France, in 1924 the Federation international de bobsleigh et de tobogganing (FIBT) was in its first year (Federation, 2016b, 2016d). The original sport included only the 4-man discipline and it wasn't until Lake Placid hosted the Olympics in 1932 that the 2-man discipline was formalized in competition (Federation, 2016b). By the 1950's the need for athleticism in the sport began to be realized and physical training of the athletes involved became a year-round endeavor (Federation, 2016b). Year-round training became necessary because the physical advancement of athletes' speed, power, and strength relies on consistent training so that the principle of reversibility in training is largely avoided (M. H. Stone, Stone, & Sands, 2007).

For most of the sport's existence, continental and world championships as well as the Olympics were the only measure of team and athlete success (Federation, 2016b). Throughout recent history the United States of America (USA) men's bobsled team has largely been unsuccessful in championship competition compared to the Swiss and Germans. While female bobsled athletes and results are not within the scope of the present study, the USA women's team has won half of all twelve Olympic medals in 2-women bobsled since it's addition to the Olympics in 2002 (Committee, 2016). By comparison, the USA men's bobsled team has won only four 4-man bobsled medals and one 2-man bobsled medal in the last 50 years of Olympic competition (Committee, 2016). In World Championship competition USA men's 4-man teams have won only nine of the available 108 medals, and only four of the more than 100 medals awarded in 2-man bobsled (Committee, 2016). Since men's bobsled competitions have existed longer throughout history, the competition is generally deeper, making it important for the USA Bobsled and Skeleton federation to recruit athletes from other popular sports. This may lessen the ability of the US federation, as compared to other European countries' federations, to take a long-term athlete development (LTAD) model of training for their athletes.

Status of Bobsled as a Sport

Since the 1980's, the World Cup series of bobsled competitions has been added and the FIBT has been renamed: International Federation of Bobsleigh and Skeleton (IBSF) (Federation, 2016d). The addition of the World Cup series, currently called the Bavarian Motor Works (BMW) IBSF World Cup, provides more race opportunities for participating nations and more track diversity annually than was encountered in previous generations (Federation, 2016b). The current tracks regularly in use for the BMW IBSF World Cup are as follows: Whistler, BC, Canada; Calgary, AB, Canada; Park City, UT, USA; Lake Placid, NY, USA; LaPlagne, France; St. Moritz, Switzerland; Winterberg, Germany; Koenigsee, Germany; Altenberg, Germany; Igls, Austria; and Sochi, Russia (Federation, 2016a). There are also lower level bobsled circuits entitled the Europa Cup and North American Cup, which both provide opportunity for developmental athletes to train and compete on various tracks used within the BMW IBSF World Cup (Federation, 2016f).

Regulations in the Sport of Bobsled

In an attempt to promote fair and equitable competition, the IBSF provides an updated rulebook each year which outline various regulations for the crew, sleds and their components, and tracks that will be raced on in that competitive season (Federation, 2016e). Each competitive bobsled season is contested during one winter, usually starting in December of one calendar year and ending in February or March of the following calendar year (Federation, 2016f).

Track Regulations

While each track is individual in its vertical profile and number, severity and order of turns, there are certain aspects of each track that are similar, especially regarding the start ramp (Federation, 2016a, 2016e). The competition length of each track varies between roughly 1200-1800m with the start ramp always constituting the first 65m of track (Federation, 2016a, 2016e). By IBSF rule, the first 15m of each track must be an even two degrees downhill and at the end of the first 15m there is a timing eye which starts the competition clock when the nose of the sled first crosses the 15m line (Federation, 2016e). After the first 15m, grooves beginning start at the start block continue for some track-specific distance down the start ramp and the profile of the start ramp is left to the discretion of the individual competition sites and may not be uniform (Federation, 2016e). The second timing eye exists 65m from the starting block and 50m from the first timing eye (Federation, 2016e). It is this eye that records the start time as the time taken in the 50m fly zone as the start time for the bobsled race (Federation, 2016e). Some tracks use multiple timing eyes placed close in sequence at the 65m line to get an estimate of instantaneous velocity at the end of the start ramp while other tracks use a third timing eye further down the track, occasionally by as much as 100m from the 65m eye to get an estimate of start velocity (Federation, 2016a). This discrepancy will be discussed in further detail in the analyses within the present study.

Sled and Crew Regulations

The IBSF provides and monitors sleds, crews and their protective equipment to ensure they fall within strict regulations of size, shape, and mass to maintain fair competition (Federation, 2016e). Most relevant to the present study are the weight limits set on sleds and their crews. The shape and interior of the sled is such that various sizes of athletes could theoretically fit within the sled and navigate tracks safely, but because of the rules in place for weight minima and maxima for 2-man and 4-person bobsled the constraints on the mass of the athletes necessitate analysis.

In 2-man bobsled the minimum empty sled mass is 170kg while in 4-man bobsled the empty sled weight minimum is set at 210kg (Federation, 2016e). The maximum weight of the crew, all their gear and apparel, and the sled together in 2-man bobsled is 390kg while in 4-man bobsled it is 630kg (Federation, 2016e). Under the assumption that sleds are manufactured to be able to get below minimum empty sled weight, with the option of adding secured weights within the sled, as most currently are in the USA, the maximum allowable crew weight, including apparel and protective gear, for 2-man bobsled is 220kg and for 4-man bobsled is 420kg (Federation, 2016e). Thus, an average maximum weight per athlete while wearing protective gear and race apparel is 110kg for 2-man bobsled and 105kg for 4-man bobsled.

Considerations for Success in Bobsled Racing

There are a multitude of factors affecting success in bobsled racing. They include friction relationships between the sled runners or other sled surfaces and the ice, the aerodynamics of the sled and crew, driving skill of the pilot and sled pushing ability of the whole crew. Further, there are day-to-day changes in ice condition and weather that add complex layers of variability in predicting finish times in the sport of bobsled (Braghin, Cheli, Maldifassi, Melzi, & Sabbioni, 2015; Rutty, Scott, Steiger, & Johnson, 2015).

Push Start Relationship to Finish Time

One of the many factors that influence bobsled racing success and finish times is the push start (Morlock & Zatsiorsky, 1989; Smith, Kivi, Camus, Pickels, & Sands, 2007). As mentioned previously, the push start is measured by both time taken to cover a 50m fly zone, starting 15m from the starting block, and by velocity after the completion of the 50m fly zone (Federation, 2016e). It is widely recognized in the bobsled racing community that a fast push start is a necessity for fast finish times and that there is a direct positive relationship between the two variables. The magnitude and details of that relationship are not widely understood within the bobsled community, however, and there have only been a small handful of studies to date which have investigated this relationship in sliding sports leaving no data for many of the bobsled tracks (Brüggemann, Morlock, & Zatsiorsky, 1997; Morlock & Zatsiorsky, 1989; Smith et al., 2007; Zanoletti, La Torre, Merati, Rampinini, & Impellizzeri, 2006).

Most studies investigating the relationship of the start and finish in sliding sports find a moderate relationship between push start time and finish time in men's bobsled as well as other sliding sports. Morlock and Zatsiorsky found a statistically significant moderate correlation (r = .46) between push time and finish time specific for the Calgary bobsled track (Morlock &

Zatsiorsky, 1989). Smith and colleagues found that nearly 40% of the variability in race finish time was predicted by start time ($r = .63$) (Smith et al., 2007). Zanoletti and colleagues found similar results among skeleton athletes across various tracks but data were compiled for the World Cup skeleton races over one season, rather than analyzed on a track-by-track basis (Zanoletti et al., 2006). An analysis of the 1994 Winter Olympic Games in Lillehammer, resulted a positive relationship between push time and finish time in bobsled as well (Brüggemann et al., 1997). Interestingly, although a relationship between finish time and start time was apparent from the images in a study by Larman the authors reported no relationship and even downplayed the importance of the start during the 2007 World Championships, which they studied (Larman, Turnock, & Hart, 2008). However, using publicly available data a non-significant but practically meaningful relationship is identifiable ($r \approx .3$, $p \approx .2$). The authors of this studied also left numerous errors within the text of the article and appeared to only loosely apply the scientific process while drawing conclusions from their data. Specifically, these authors made conclusions regarding the "best combination of height and body weight" exclusively using those characteristics found in the winner of the male and female races (Larman et al., 2008). The confounding variables in this situation are numerous and thus drawing useful information from the study by Larman and colleagues is difficult (Larman et al., 2008). In any case, there have been no published data concerning the other numerous BMW IBSF World Cup bobsled tracks currently in use today regarding their individual relationships between start time and velocity to finish time, in 2- and 4-man bobsled racing (Brüggemann et al., 1997; Morlock & Zatsiorsky, 1989; Smith et al., 2007; Zanoletti et al., 2006).

Physical Measurement of Push Athletes and Relationships to Push Start Characteristics

It has been postulated that bobsled athletes must possess the ability to produce high forces rapidly and have the capacity for both high rates of sprint acceleration and top speed running (DeWeese, Sams, & Serrano, 2014; Maiorca, Osbeck, Amico, Balocki, & Rundell, 1995; Osbeck, Maiorca, & Rundell, 1996). Accelerative capability and vertical jump performance have both been individually correlated to push times from the brake position and the right side push, and the right side push alone, respectively (Maiorca et al., 1995; Osbeck et al., 1996). This underlines the need for high acceleration ability and high power output in push athletes.

Given the constraints on sled weight outlined previously, it is likely advantageous to maximize crew weight. This would allow for minimization of sled weight (to the sled minimum in the respective disciplines) while still allowing for near maximum sled plus crew and gear total weight, which is optimal for maintenance of momentum throughout the descent of the track. Given that athletes generally can move faster and accelerate a fixed system mass when resisted by less weight, (Kraska, Ramsey, Haff, et al., 2009) it is a reasonable assumption that a maximum weight crew pushing a minimum weight sled would provide for the best possible push times and velocities (DeWeese et al., 2014).

Moreover, because athletes' ground contact times are limited in sprint running, (Weyand, Sternlight, Bellizzi, & Wright, 2000) and bobsled athletes necessarily possess relatively large body masses, high forces must be achieved quickly during each foot strike of the acceleration. Thus, high rates of force development (RFD) are imperative. In sprinting without resistance, relative strength levels are correlated to sprinting ability over short distances (Seitz, Reyes, Tran, de Villarreal, & Haff, 2014). Because of the necessity for relatively massive athletes in bobsledding (usually 90-110 kg), this in turn logically requires high absolute strength as well as high absolute power outputs. Further, high leg power, sprinting-specific joint angle strength, and stiffness are beneficial attributes to sprinters and may also be important for bobsled push athletes (Bret, Rahmani, Dufour, Messonnier, & Lacour, 2002; Chelly & Denis, 2001).

Details of Proposed Research

Push Athlete Characteristics

While there are numerous studies relating strength, power, and tissue stiffness to sprinting ability, (Bret et al., 2002; Chelly & Denis, 2001; Comfort, Bullock, & Pearson, 2012; J. B. Cronin & Hansen, 2005; Dal Pupo, Arins, Guglielmo, Silva, & Santos, 2010; Hudgins, Scharfenberg, Triplett, & McBride, 2013; Lockie, Murphy, Knight, & de Jonge, 2011; Marques & Izquierdo, 2014; McBride et al., 2009; Sleivert & Taingahue, 2004; Weyand, Sandell, Prime, & Bundle, 2010) there exists a paucity of research on the physical abilities specific to bobsled push athletes (Morlock & Zatsiorsky, 1989). The reason for the paucity of research on bobsled athletes may be partly because of the very small participating population worldwide. The impact of advancing research in this area could be great for the sport because in the men's sport in the Olympics there are six total medals available in bobsled competition as well as six medals each non-Olympic year in World Championship competition (Committee, 2016). It is presently unknown, given the current state of the literature, what sprint times, strength levels, and capacities for RFD are needed to become a successful push athlete. Even more limited are the numbers of studies that attempt to provide talent identification means for bobsled national teams, or provide meaningful benchmarks for which coaches, practitioners, and athletes should be seeking to attain to maximize bobsled pushing performance.

Purpose. The data from the present study provided means for the national team selection committee in the USA to better identify future successful push athletes before their initial exposure to the sport.

The present study elucidated the relationship of the current 8-item bobsled combine test to sled pushing ability, as measured by the push track performance. The eight items include: 15m, 30m, and 60m sprints with a 1m fly-in, a 30m fly with a 16m fly-in, standing broad jump into a sand pit, 7.26 kg underhand shot toss from a shotput toe-board, three repetition maximum back squat and a one repetition maximum power clean. The sum of the scores for the respective events, the sum of the 6-item combine items' scores, and the individual scores for each event, as well as body mass, were correlated to push track performance in national solo-push competition and a linear regression for each comparison was carried out. The study also attempted to identify meaningful differences in combine measurements and body mass between successful and less successful push athletes as groups.

Limitations. The present study was primarily limited by the size of the data set, given the constraints on the participating population. There are usually less than 20 athletes per year that participate in each of the required combine batteries and the preliminary push championships, thus limiting sample size. Further limiting was the changing nature of the push championship protocol on an annual basis, at the coaches' discretion. This makes year-to-year comparison or pooling of data impossible.

Delimitations. The population of the proposed study has been limited to those athletes who receive an invitation to the preliminary push championships by the USA Bobsled national team coaching staff. Combine data from these athletes was collected from their combines where they competed against other athletes who may not have been invited. The athletes who were not invited did not have their combine data analyzed because it is important to set the threshold of performance reasonably high so that the population being studied has reasonable homogeneity. And, because of the limited sample size, though multiple regression analysis could be useful in the future for predictive purposes, it isn't feasible without more years' data with more consistent measurement of athlete performance.

Significance. The analysis within the present study can help national coaching staff to better identify push athlete characteristics that are more predictive of push track ability than the current protocol. The present study could allow a more time-efficient or cost-effective means of identifying talent, as opposed to the current combine battery. It is possible that this method of talent identification could also be used as a monitoring tool.

Push Start Time and Velocity Relationship to Finish Time

There are many variables that affect finish time outside of the initial push start, including: driving, materials weight and quality, environmental factors, and riding position of the athletes, which affects aerodynamics (Brüggemann et al., 1997; Federation, 2016c, 2016e; Rempfler & Glocker, 2016). Even with the numerous variables affecting finish time, at the BMW IBSF World Cup level, it is generally accepted that there is some level of positive and direct relationship between the push start and finish time (Brüggemann et al., 1997; Federation, 2016c; Morlock & Zatsiorsky, 1989). The paucity of research in this area necessitates further research on the intricacies of the relationships and the potential predictive ability of the push start variables and finish times.

Purpose. The proposed study will examine the reliability characteristics, and the relationship between on-ice push times and velocities, and finish times, elucidating this relationship for more meaningful discussion and coaching decision-making based on the track specific relationships. The explored interactions will be between start time, and velocity, and various down track splits including the finish time, for each track on which bobsled races are currently contested in the BMW IBSF World Cup.

Limitations. The proposed study is again limited by sample size due to the exclusive nature of top tier sport. There are more tracks than there are races, each year at the BMW IBSF World Cup level, thus the two years that will be analyzed in the proposed study may not be able to analyze each track over multiple races. Further, conditions at each track change with the weather, meaning that track conditions from year to year may not be consistent. This may change the relationship of the start variables to the finish time.

There is no standardized means of measuring start velocity. This is especially apparent in certain tracks where start velocity is an estimate based on multiple timing eyes that are many meters apart. This will be noted when possible, but may cause the relationship between start velocity and finish variables to be misrepresented.

Delimitations. The author of the proposed study has chosen to analyze only 2014-15 and 2015-16 seasons of the BMW IBSF World Cup 2-man and 4-person bobsled races to maintain the feasibility of the project. Certain tracks start velocity analyses may be thrown out for the reasons discussed above.

Significance. The elucidation of the exact relationships of velocity and start time on each of the BMW IBSF World Cup bobsled tracks may allow coaching staff and selection committees to identify which characteristics are most important for successful finish times and thus winning at the international level. Further, if it can be identified where on each track the relationship of split times to start variables changes, coaches will be able to more rationally analyze the time sheet data that is provided during practice and competitive sliding sessions and make better decisions based on their analysis.

Definitions

1m Fly-In: A one-meter portion of flat running track demarcated on either side with athletic tape, that allows a bobsled athlete a short space to start within before breaking through the first timing gate at roughly 15 inches tall, which contributes to the timing of the 15m, 30m, 45m and 60m sprints. This fly-in zone is the only opportunity for bobsled athletes to begin producing momentum before the timing has started. The athlete must start with one heel of one foot in front of the first tape line on the ground.

1RM: See “One Repetition Maximum.”

15m Fly Zone: A portion of bobsled track placed between the start block and a timing eye 15m away from the start block, that is untimed, allowing for the creation of momentum before the nose of the sled break the first timing eye and the elapsed racing time starts. This zone is always negative two degrees downhill from the starting block.

15m Sprint: A sprint of 15m in length preceded immediately by a one-meter fly-in. Timing is started the instant the first timing gate is tripped at approximately 15 inches tall, and elapsed time is measured when the athlete breaks through the second timing gate, 15m from the first, placed at approximately 40 inches tall. Scored 0-100 with a maximum score being awarded at 2.05 seconds.

16m Fly-In: A 16m portion of flat running track demarcated on one side by a tape line on the ground and on the other by the second timing eye, placed at approximately 40 inches high, in a series of 5 timing gates. This fly-in phase is the only opportunity for the bobsled athlete to accelerate before entering the 30m timing zone for the 30m fly test in the combine.

2-Man: See “2-Man Bobsled.”

2-Man Bobsled (n. sport): A winter sport in which teams of two male athletes compete in sliding, for time, down man-made, iced tracks usually about one mile in length, contained in a 2-man bobsled. [(see “2-Man Bobsled (n. vehicle)” definition].

2-Man Bobsled (n. vehicle): A sled composed of a frame, cowling, runners, a handheld steering device, and tooth-like brakes, large enough to enclose a driver and a brakeman.

30m Sprint: A sprint of 30m in length preceded immediately by a one meter fly-in. Timing is started the instant the first timing gate is tripped at approximately 15 inches tall, and elapsed time is measured when the athlete breaks through the third timing gate, 30m from the first, placed at approximately 40 inches tall. Scored 0-100 with a maximum score being awarded at 3.55 seconds.

30m Fly: A sprint of 30m in length, preceded immediately by a 16m fly-in. Timing is started the instant the second timing gate is tripped, placed 15m from the first timing gate at a height of approximately 40 inches, and elapsed time is measured when the athlete breaks through the fourth timing gate, placed 45m from the first at a height of approximately 40 inches. This is performed simultaneously to all other sprint measurements within a combine.

3RM: See “Three Repetition Maximum.”

3RM Back Squat: See “Three Repetition Maximum Back Squat.”

4-Man: See “4-Person Bobsled.”

4-Man Bobsled: See “4-Person Bobsled.”

4-Person Bobsled (n. sport): A winter sport in which teams of four athletes compete in sliding, for time, down man-made, iced tracks usually about one mile in length, contained in a bobsled. [(see “4-Person Bobsled (n. vehicle)” definition]. Since the 2014-15 BMW IBSF World Cup season, female pilots have competed in the same competitions as men, necessitating the switch from the former “4-Man” terminology.

4-Person Bobsled (n. vehicle): A sled composed of a frame, cowling, runners, a handheld steering device, and tooth-like brakes, large enough to enclose a pilot and three push athletes.

45m Sprint: A sprint of 45m in length preceded immediately by a one meter fly-in. Timing is started the instant the first timing gate is tripped at approximately 15 inches tall, and elapsed time is measured when the athlete breaks through the fourth timing gate, 45m from the first, placed at approximately 40 inches tall. Scored 0-100 with a maximum score being awarded at 5.10 seconds.

50m Fly Zone: The measured length of the push start in 2-man and 4-person bobsled racing. Time measurement begins when the nose of the sled breaks through the first timing eye, placed 15m from the start block, approximately six inches high. Time measurement is ceased when the sled nose breaks through the second timing eye, placed 65m from the start block, approximately six inches high.

6-Item Combine: A battery of six physical tests scored from zero to 100, used in evaluating and monitoring the ability and preparedness of athletes to push a bobsled. The 6-item combine for bobsled, at the time of research was composed of the 15m sprint, 30m sprint, 60m sprint, 30m fly, standing broad jump, and underhand shot toss. It has since been modified to exclude the 60m sprint and include the 45m sprint.

60m Sprint: A sprint of 60m in length preceded immediately by a one meter fly-in. Timing is started the instant the first timing gate is tripped at approximately 15 inches tall, and elapsed time is measured when the athlete breaks through the fifth and final timing gate, 60m from the first, placed at approximately 40 inches tall.

8-Item Combine: A battery of eight physical tests scored from zero to 100, used in evaluating and monitoring the ability and preparedness of athletes to push a bobsled. The 8-item combine for bobsled, at the time of research was composed of the 15m sprint, 30m sprint, 60m sprint, 30m fly, standing broad jump, and underhand shot toss, three repetition maximum back squat, and one repetition maximum power clean. It has since been modified to exclude the 60m sprint and include the 45m sprint.

Acceleration: The rate of change of velocity per unit time.

Back Squat: A resistance training exercise wherein an athlete stands erect, bends at the hips, knees, and ankles, performing a squat while holding a barbell on their back. Also, see "Three Repetition Maximum Back Squat."

Bavarian Motor Works (BMW): The auto manufacturing company that holds the title sponsor for the World Cup series of bobsled races.

Block: See "Start Block."

BMW: See "Bavarian Motor Works (BMW)."

BMW IBSF Bobsled World Cup: A series of seven to nine races hosted across the northern hemisphere, annually, which provide competition opportunity between the world's best bobsled teams, on diverse tracks. Provides a portion of the rankings, qualification, and seeds for the World Championships and Olympics bobsled races.

Bobsled (n. sport): A winter sport in which teams of two or four athletes compete in sliding, for time, down man-made, iced tracks usually about one mile in length, contained in a bobsled. [(see "Bobsled (n. vehicle)" definition].

Bobsled (n. vehicle): A sled composed of a frame, cowling, runners, a handheld steering device, and tooth-like brakes, large enough to enclose 2- or 4- person teams of athletes.

Bobsled Push Track: A rubberized or ice straight track with rails akin to a small railroad track suitable for a bobsled on wheels to roll on, or with grooves similar to a conventional bobsled track. Usually push tracks have a vertical profile similar to that of bobsled tracks start ramps, but then often run immediately uphill to assist in decelerating the rolling sled and returning it to the starting position. Other braking mechanisms often also exist.

Bobsled Track: The physical structure on which the sport of bobsled is competed. Usually about one mile in length, composed of 12-20 turns, outfitted with timing eyes for race measurement, and refrigeration to ensure the ice surface is suitable for competition.

Brakeman: One of two or four athletes who pushes but does not drive the sled. Within the bobsled community the word 'brakeman' is taken to mean all other athletes except the driver. Specifically, the single athlete in the back of the sled who pulls the brakes at the end of the run is termed brakeman. While in a 4-person sled, the second and third push athletes may also be referred to as 'brakemen' although they do not interact with the brakes of the sled.

Broad Jump: See "Standing Broad Jump."

Clean: A weightlifting exercise, in which an athlete moves a barbell from the floor to a "catch" position across the deltoids in one continuous motion.

Combine: A battery of either six or eight physical tests used to evaluate and monitor an athlete's and ability and preparedness to push a bobsled. Also, see "6-Item Combine, 8-item Combine, Mini-Combine."

Cowling: A fiberglass or carbon-fiber exterior shell surrounding all internal components of a bobsled, including its crew. Usually designed with aerodynamics in mind.

Crew: Usually refers to the three non-driving push athletes (brakemen) in a 4-person team of bobsled athletes.

Europe Cup: A European circuit of bobsled races usually considered one step below the BMW IBSF World Cup and consisting of competition on all tracks in France, Germany, Switzerland, Latvia, and Austria. Scores from this cup contribute to overall world ranking for bobsled pilots and nations but are not weighted as heavily as the World Cup.

Federation: A governing body a sporting organization and all its components, staff, and athletes, that manages and competes in competitions, creates sporting rules and monitors their adherence, and coordinates use of its facilities. Federations exist at national and international levels in the sport of bobsled.

Federation international de bobsleigh et de tobogganing (FIBT): The original international governing body of the sport of bobsled and skeleton. Now, see "International Bobsleigh and Skeleton Federation (IBSF)."

FIBT: See "Federation international de bobsleigh et de tobogganing (FIBT)."

Finish Time: The complete elapsed time taken to navigate the bobsled track. Time begins when the nose of the bobsled breaks the timing eye 15m from the start block and ends when the nose of the bobsled breaks the final timing eye on the track, usually 1200-2000m from the first timing eye.

Fly Zone: A given portion of track (either flat running track, as in combines, or on ice, as in bobsled racing) allotted for athletes to build momentum before beginning timing or a portion of timing of a contested event. Also, see “15m Fly Zone, 50m Fly Zone, 1m Fly-In, 16m Fly-In.”

Force: An interaction that, when unopposed, will change the motion of an object. Usually measured in Newtons.

Grooves: See “Start Grooves.”

IBSF: See “International Bobsleigh and Skeleton Federation (IBSF).”

International Bobsleigh and Skeleton Federation (IBSF): The current international governing body of the sport of bobsled and skeleton. Formerly, the FIBT.

Load (Loading): The act of 2- or 4-person crews loading

Long Term Athletic (Athlete) Development (LTAD): A model of youth and athlete development that recommends appropriate engagement in the physical development of the young athlete to reduce risk of injury and provide performance enhancement through sound pedagogical approaches. (Lloyd et al., 2016)

LTAD: See “Long Term Athletic (Athlete) Development (LTAD).”

Materials: A term usually used in the sport of bobsled to refer to all physical materials included in the bobsled race as they relate to racing performance.

Mini-Combine: A small battery of tests used to monitor or evaluate an athlete’s ability or preparedness to push a bobsled. The battery includes a 15m sprint, 30m sprint, and one repetition maximum power clean. Only athletes who have previously scored 675 points or higher on the 8-item combine are tested using the mini-combine protocol.

National Team (USA): The team of usually 11 push athletes and three pilots named to represent the United States of America at the highest level for the competitive season in the sport of bobsled.

National Team Selection Committee: A committee composed of United States of America Bobsled and Skeleton head coaches and administrators who are responsible for evaluating and selecting the national team at the onset of each BMW IBSF World Cup competitive season.

National Push Championships: An invite-only test of athletes' individual bobsled pushing ability, usually hosted on land during the first two years of a Winter Olympiad, and hosted on an ice push track in the second two years. Only former national team athletes and those who perform to a coach-selected standard during Preliminary Push Championships are asked to join. Athletes push a sled of weight determined by National Team coaching staff, over a distance also determined year-on-year by National Team coaching staff. Placing at this competition is used by pilots to recruit teams for National Team Trials, and for the National Team Selection Committee to select National Team members.

North American Cup: A North American circuit of bobsled races usually considered one step below the BMW IBSF World Cup. The four tracks contested in this Cup are located in Whistler, BC and Calgary, AB in Canada and in Park City, UT, and Lake Placid, NY, in the United States of America. Points are awarded from this cup at lower level than those from the BMW IBSF World Cup and contribute to overall world ranking.

One Repetition Maximum: The most weight an athlete can lift for one exercise movement completion.

One Repetition Maximum Power Clean (n. bobsled combine item): A test used to estimate absolute power in the combine protocol of United States Bobsled and Skeleton. While it is termed “power” clean, there is no objective standard used other than those of the traditional clean exercise, with no measurement or assessment of depth of bar-receiving position. Scored 0-100 with a maximum score being received at 150kg.

Power: Work rate. Alternatively, force, multiplied by velocity.

Power Clean: A weight training exercise referring to any variant of the clean in which the lifter does not receive the bar in a full squat position. Usually returning to standing once bar is received without knees flexing below 90 degrees in the catch portion of the exercise is considered a power clean. Also, see “Clean.”

Preliminary Push Championships: An invite-only solo-push competition on a rubberized push track, hosted annually by the Lake Placid Olympic Training Center and United States Bobsled and Skeleton in order to determine the best future push athletes to be invited to the National Push Championships. This is the second stage in recruiting new athletes in the United States, and selections for invite are based on 6-item combine scores. Athlete push once from each position on the sled (brakes, right, and left), and are allotted one additional self-selected-position push to replace the previous push from that position.

Push Athlete: A bobsled athlete responsible for part of the initial acceleration of the sled and for riding in the sled down the bobsled track.

Push Track: See “Bobsled Push Track.”

Push Start: The portion of the bobsled race before the second timing eye, placed 65m from the start block, composed of all bobsled athletes pushing to accelerate the sled, and loading into the sled.

Push Start Time: The time taken to travel the 50m between the first and second timing eyes in a bobsled race, placed 15m and 65m from the start block.

Push Start Velocity: The velocity of the sled, usually containing the seated crew, usually taken at about 65m from the start block, or near the end of the push start. There is no uniform way of measuring velocity

Rate of Force Development: The rate at which muscular force can be applied to an object or body.

Repetition Maximum: The most weight an athlete can lift for a defined number of exercise movements.

Reversibility: A principle of training stating that athletes may lose the enhancement of performance due to training, when training ceases, and vice versa.

Riding Position: The body position of the crew within the sled during the bobsled race, which can have an impact on overall aerodynamics of the sled.

Runner(s): Tightly controlled and highly monitored, long, rounded, steel interchangeable components of the bobsled, all of which can articulate independently within the sagittal plane or as pairs in the frontal plane, and provide the surface and interaction with the ice, on which the bobsled slides. Only the front pair of runners can articulate in unison in the transverse plane to allow the steering mechanism to function.

Selection Committee: See "National Team Selection Committee."

Shot Toss: See "Underhand Shot Toss."

Skeleton: A winter sliding sport in which an athlete competes, for time, in driving a small open-air sled, in the prone position, down man-made iced tracks usually about one mile in length.

Solo-Push: A push of a bobsled on a performed on a push track by one athlete, independently. This can be performed from the driver's position or any of the three 4-person positions (brakes, right, and left) on the sled, and is the principal component of the Preliminary Push Championships as well as a portion of the National Push Championships.

Speed: The rate at which someone or something moves. A scalar quantity (without specific direction). Usually measured in m/s or km/hour.

Split Time: The elapsed time between the first timing eye in a bobsled race and any intermediate timing eye between the 65m timing eye and the finish timing eye.

Standing Broad Jump (n. bobsled combine item): A test used to estimate power by performing a single explosive jump for distance into a sand pit. An athlete stands with feet adjacent to each other and stationary on the edge of a long/triple jump sand pit, leaps forward maximally and lands in a self-selected manner, with the closest mark in the sand being used as the mark for measurement. Measurement is taken from the mark to the edge of the sand pit in meters. Scored 0-100 with 3.35m being awarded 100 points.

Start Block: A composite wood block, placed at the top of an iced bobsled track or at the beginning of a push track, used by athletes to set their feet the first explosive movements of a bobsled push.

Start Grooves: Two parallel narrow cuts within the ice start ramp on a bobsled track designed to guide the runners of the sled in a straight path. Start grooves, usually about 16mm wide, start at the starting block and continue at least 50m down the track, thereby extending at least 35m into the timed 50m fly zone.

Start Ramp: The inclined portion of the bobsled track on which athletes perform the push start. The start ramp is composed of a start block, start grooves, a 15m section of 2 degrees downhill, and then 50m of track designer-selected downhill, with two pairs of timing eyes placed at 15 and 65m.

Start Time: See "Push Start Time."

Start Variables: See "Push Start Time" and "Push Start Velocity."

Start Velocity: See "Push Start Velocity."

Strength: A measure of one's ability to produce force.

Three Repetition Maximum: The most weight an athlete can lift for three exercise movement completions.

Three Repetition Maximum Back Squat (n. bobsled combine item): The most weight an athlete can lift while performing the back squat exercise for three repetitions. Within the bobsled combine battery, the only measure of completion for this exercise is visual assessment by a strength and conditioning professional or bobsled coach, with no clear objective standard for depth, bar placement, or lifting equipment worn during its completion. Scored 0-100 with a maximum score being received at 200kg.

Timing Eye(s): Optical measurement devices used to register when an object has broken one eye's view of the other, which can be used to measure time elapsed between two sequential timing eye pass-throughs.

Timing Gate(s): Optical measurement devices used to register when a bobsled athlete has broken one gate's view of the other, which can be used to measure time elapsed between two sequential pass-throughs.

Toe Board: The physical structure usually used in restraint of a shot put athletes foot during the track and field event of shot put. In bobsled, used as a device for athletes to push off of while performing the underhand shot toss exercise as a component of the combine. Measures approximately 10cm tall, 11-30cm deep, and 1.21m across.

Track: See “Bobsled Track.”

Underhand Shot Toss (n. bobsled combine item): A test used to measure sport-specific power in bobsled and skeleton by throwing a shot for distance from between the legs with two hands. Standing on a toe board with feet stationary and adjacent, athletes swing the shot (7.26kg) between their legs with two hands and throw it forward for distance into the throwing sector. Measurement is taken, in meters, from the closest edge of the toe board to the closest mark in on the ground left by the landing shot. Scored from 0-100 with a maximum score being awarded for 18m.

United States Bobsled and Skeleton Federation: The former name of the governing body for the sport of bobsled and skeleton in the United States of America. Now, named: United States of America Bobsled and Skeleton.

United States of America Bobsled and Skeleton: The official federation and governing body for the sports of bobsled and skeleton in the United States of America.

USABS: See “United States of America Bobsled and Skeleton.”

USBSF: See “United States Bobsled and Skeleton Federation.”

Velocity: The rate at which someone or something moves in a direction. A vector quantity (with specific direction). Usually measured in m/s or km/hour.

World Cup: See “BMW IBSF Bobsled World Cup.”

CHAPTER 2

REVIEW OF LITERATURE

Introduction

The sport of bobsleigh, also known as bobsled, originally a perilous, unscientific, recreational sport for wealthy, winter sport enthusiasts, has evolved over the last century into a highly competitive Olympic sport with all the dressings of technology, money, and year-round training that come with it (Federation, 2016b). While there has been a dramatic increase in the number of athletes participating, as well as the resources poured into these teams of athletes, the scientific literature is still relatively scant on many aspects of the sport. Part of this may be due to individual countries' ambitions to conceal their engineering and sport science data to safeguard their own position as an international power in the sport of bobsled.

History of Bobsled as a Sport

The first bobsled track was built in 1902 in St. Moritz, Switzerland, although some informal racing had taken place on snowy public roads since 1884 (Federation, 2016b). Formal racing started only 4 years earlier than the construction of the first official bobsled track in St. Moritz, and this competition was carried out on the Cresta Run by the local bobsled club (Britannica, 2010). Within 15 years of the St. Moritz track construction, bobsleigh races were formalized across European winter resort towns. To gain speed, the crews atop these sleds would bob back and forth, giving rise to the name of the sport (Federation, 2016b).

The Federation internationale de bobsleigh et de tobogganing (FIBT) was formed in 1923, followed by the inclusion of bobsled in the inaugural Winter Olympics in 1924, hosted in Chamonix, France (Federation, 2016b, 2016d). Eight years later, a two-man bobsled event was added into the Olympic Games (Federation, 2016b). Through the 1920's, 1930's and 1940's there was no formal training of athletes for the sport, and there was no sled or crew weight limit, thus, participation was generally limited to wealthy overweight tourists and avid hobbyists (Federation, 2016b).

By the late 1940's and early 1950's two major changes took place that made it necessary for well-trained athletes to participate in the sport to have strong push starts at the beginning. First, wartime had ended sufficiently long enough for economic prosperity to begin flourishing across Europe, (Roser, 2016) allowing greater expendable resources to be invested in recreation and sport. Second, a rule change in the sport set a maximum crew and sled weight (Federation, 2016b). Both things taken together meant an investment in athletic development became necessary for successful competition in the sport of bobsled at the international level.

From the inception of the winter Olympics until the 1980's when World Cub bobsled competition began, the only formal international competitions were European and World Championships, hosted on non-Olympic years and the Winter Olympics, hosted every 4 years starting in 1924 (Federation, 2016b). While the USA had some success in the early sport it has been largely the countries responsible for hosting the major competitions in the Alps that have been the most successful (Committee, 2016; Federation, 2016b). Germany and Switzerland have been the sport's powerhouses since its founding (Committee, 2016; Federation, 2016b).

The modernization of the sport accelerated from the 1950's through the 1980's. Sleds transitioned from having wooden components to metal and fiberglass components. Steering mechanisms and aerodynamic profiles of the sleds became more advanced and regulations for the various sled components also advanced rapidly (Federation, 2016b). Large tracks made from concrete with interior refrigeration for extended sliding seasons became the norm (Federation, 2016b). By 1984 the rules for bobsled frame design were standardized, and after another 20 years, the rules for runner steel, which are in place today, became standard (Federation, 2016b, 2016e).

Current Status of the Sport of Bobsled

Currently the sport is performed at various competitive levels and on multiple international competitive circuits around the world, hosted by more than a dozen individual bobsled tracks spread across 11 countries. The technology included in sled and equipment design has quickly advanced with the technological advances common to the 21st century (Lee, Kim, Lee, Kil, & Hong, 2015; Rempfler & Glocker, 2016). Likewise, training for bobsled is now managed by teams of sport scientists, sport coaches, nutrition experts, and medical staff, similar to professional sporting organizations (DeWeese et al., 2014; Federation, 2017; Lee et al., 2015; Rempfler & Glocker, 2016).

Bobsled Competition Levels. The BMW IBSF World Cup racing circuit is the highest level of annual competition and culminates in the IBSF World Championship or the Olympic Games, annually (Federation, 2016f). The Europe Cup and the North American Cup racing circuits rank beneath the World Cup level competition (Federation, 2016f). There is currently no singular championship race on the North American Cup, while the European Championships are hosted annually on various tracks in Europe (Federation, 2016f). There exist, also, regional bobsleigh and skeleton clubs which often host local competitions or regional level championships annually (Association, 2017; Park, 2017; Quebec, 2017).

Bobsled Tracks. There are currently 15 operable bobsled and skeleton tracks in the world, however, not all of them are routinely competed on at the international level. The bobsled tracks that are usually rotated through the World Cup circuit, though they are not each included every year, include: Altenberg, Germany; Calgary, Alberta, Canada; Igls, Austria; Konigssee, Germany; La Plagne, France; Lake Placid, New York, United States of America; Park City, Utah, United States of America; Pyeongchang, South Korea (as of 2017); Sochi, Russia; St. Moritz, Switzerland; Whistler, British Columbia, Canada; and Winterberg, Germany (Federation, 2016a). The tracks that are no longer routinely competed on during international competition at the World Cup level, but are still in use are: Lillehammer, Norway; Nagano, Japan; and Sigulda, Latvia (Federation, 2016a). Further details regarding the tracks can be located in Table 2.1.

Table 2.1. Bobsled Track Data

Bobsled Track Location	Competition Length (m)	Maximum Gradient	Average Gradient	Vertical Drop (m)	Number of Curves
Altenberg, GER	1413	15.0%	8.7%	122.2	17
Calgary, CAN	1494	15.0%	8.0%	121.0	19
Igls, AUT	1207	18.0%	9.0%	124.0	14
Konigssee, GER	1251	Unreported	9.0%	120.0	16
La Plagne, FRA	1508	14.0%	8.0%	124.0	19
Lake Placid, USA	1455	20.0%	9.0%	128.0	20
Park City, USA	1335	15.0%	8.0%	104.0	15
Pyeongchang, KOR	1376	25.0%	9.5%	117.0	16
Sochi, RUS	1500	22.0%	Unreported	124.0	17
St. Moritz, SUI	1722	15.0%	8.0%	130.0	19
Whistler, CAN	1450	20.0%	9.0%	148.0	16
Winterberg, GER	1330	15.0%	9.0%	110.0	15

Adapted from http://www.ibsf.org/en/tracks. (Federation, 2016a)

Technology. The technological advances in the sport of bobsled have come from every angle, including: biomechanists, physiologists, physicists, nutritionists, materials and vehicle design engineers, NASCAR experts, sport scientists, sports medicine experts, and software designers (Berton, Favier, Agnès, & Pous, 2004; Lee et al., 2015; Morlock & Zatsiorsky, 1989; Rempfler & Glocker, 2016; Skeleton, 2017c). In the United States there are currently sport biomechanists, sport psychologists, sport physiologists, computer scientists, and engineers dedicated to the Olympic Training Center where USA Bobsled and Skeleton is housed in Lake Placid, New York, United States of America (Committee, 2017). The sports medicine staff at the same facility is comprised of chiropractors, physical therapists and athletic trainers, as well as a strength and conditioning staff with education in sport physiology and performance (Committee, 2017).

Financial and Administrative. The IBSF is comprised of 70 national federations in the sports of bobsled and skeleton (International Bobsled and Skeleton Federation, 2017). Each national federation of bobsled and skeleton is in place principally for the governance of its own competitive teams and their development and is governed dually by the IBSF and the National Olympic Committee of the respective country, both of which must conform with the Olympic Charter in order to be recognized by the IOC (Committee, 2017). The IBSF currently has an executive committee comprised of nine executives from different countries, (International Bobsleigh and Skeleton Federation, 2017c) as well as eight advisory committees each pertaining to various aspects of the sport and it's continued international growth (International Bobsleigh and Skeleton Federation, 2017a). While the IBSF is not a non-profit organization, the USA Bobsled and Skeleton Federation is currently designated as such (Federation, 2017).

In the United States of America, bobsled is not government-funded, as it is in select other countries, however the expenses incurred by the USA Bobsled and Skeleton federation have become quite substantial in the last decade, increasing from $2.2M in 2009 to $3.1M annually since 2015 (Federation, 2017). This is reflective of the state of the sport, internationally, and its continued rapid growth and development as well as the growth of economy in the US (Federation, 2017). In the US, this financial expenditure has been in large part due to increased pay for athletes, as well as increased coaching salaries (Federation, 2017).

Athlete Training. In the first nearly 75 years of the sport's existence, there was little physical training, and certainly no formal, year-round athlete training under the supervision of professional coaches (Federation, 2016b). Today, in the United States, approximately $500,000 per year are spent within USABS, on expert coaches, to improve athlete and team performance (Federation, 2017). That capital outlay does not include money spent by athletes on private strength, speed, or nutrition coaches, nor does it include money available to US athletes for college tuition and professional coaching from premier sport scientists in the sport of bobsled (Federation, 2017; University, 2017).

Currently, bobsledders train year-round with highly specialized performance coaches who are usually experts in both physiology and biomechanics as they relate to bobsled (DeWeese et al., 2014). This training is largely comprised of sprinting, pushing or pulling sleds, and resistance training specific to bobsled (DeWeese et al., 2014). There is a slowly growing field of research around the sport and the training methods utilized, but given the proprietary nature of much of the knowledge of training methods and technology surrounding the sporting equipment, within each national governing body, publications have been relatively sparse (Berton et al., 2004; Dabnichki & Avital, 2006; Koutedakis, Agrawal, & Sharp, 1998; Larman et al., 2008; Morlock & Zatsiorsky, 1989; Osbeck et al., 1996; Smith et al., 2007; Zanoletti et al., 2006). In the United States most athletes are recruited from either track and field or football, and all but one of the current national team members were competitors in one or both of those sports before becoming a bobsled athlete (Skeleton, 2017d). In other countries as well, track and field is the most common background for bobsled athletes (International Bobsleigh and Skeleton Federation, 2017b). It is this athletic background in speed/power sports that lays the foundation for all current training methods employed by the coaches today in the sport of bobsled (DeWeese et al., 2014).

General Bobsled Racing Information

Bobsled races are usually composed of two heats of racing in each discipline, with the exception of world championships and Olympics where 4 heats of each discipline are contested, usually on separate weekends (Federation, 2016f). Races in 2-man and 4-man bobsled are distinct entities, though they usually happen on sequential days on the same track for ease of training organization for all the competitors and teams (Federation, 2016f). The local race organizers follow IBSF race protocol and make known any idiosyncrasies to representatives from each team in advance of the competition (Federation, 2016e). Teams of athletes are composed of some combination of driver and push athletes and are fixed for the duration of the competition, barring any extenuating circumstances like injury or extreme illness (Federation, 2016e). Athletes generally wear similar clothing across all teams, and within teams it is generally identical matching uniforms, though various components of the protective equipment can vary even within teams (Federation, 2016e). While weather can certainly can have measurable effects on race outcome, typically the races are contested regardless of inclement weather (Federation, 2016f). Awards are disseminated immediately following the race and sled inspections (Federation, 2016e).

Bobsled Race Protocol. Specific race protocol is in place with regard to team start order, advancement to the second heat, track conditions during the race, start-specific rules, forerunners or pilot sleds, and timing systems capabilities.

Forerunners/Pilot Sleds. During training and racing the timing system and track reliability are tested by pilot sleds, also known as forerunners (Federation, 2016e). Each of the pilots of these sleds serve as a report to the track maintenance manager(s) regarding the safety and quality of the ice and the track's readiness for competition or training.

Sled Order and Timing in Sequence. For training sessions leading up to races, sleds are ordered by nation rank and grouped sequentially with other sleds from each respective nation, so that all sleds from one nation immediately follow each other. For bobsled races, sleds are ordered by draw, based on season ranking, for the first heat of each race. Once ordered, sleds depart the start block, from sled one to the end of the order, with just enough time between them to clear the track for safety. When the track is cleared, the next team of competitors has 60 seconds to break the first timing eye and start their run. If a team is not present with their sled at the starting line when the track is cleared they can be disqualified (Federation, 2016e). Or, if the team fails to start the timing of their run within the 60-second start window, they are automatically disqualified (Federation, 2016e). At the World Cup level, these start errors are very rarely an issue because of the highly-regimented routines that athletes undertake in preparing for their runs.

Advancement to, and order within, heat two of the race is determined by ranking after heat 1, with the 20th-ranked sled starting first in heat two (Federation, 2016e). In 4-heat races like Senior World Championships and the Olympic Games, sleds are re-ordered, based on rank, after each heat with only the top 20 sleds participating in the second day of two heats (Federation, 2016e).

Timing systems. All tracks have at least two timing systems running simultaneously, each measuring the time of day and the instances when the timing eyes are crossed (Federation, 2015a). It is the difference between the time taken at two sequential timing eyes which makes up a split time (Federation, 2015a). For a bobsled track to be considered for Olympic or World Championship competition hosting, both the “A” and “B” timing systems must be fully synchronized and available at all timing eye locations on the track (Federation, 2015a). Older tracks often only have available an “A” timing system at each of the split locations, from start to finish, while the “B” timing system is only present at the first timing eye placement (15m from the start block) and at the finish timing eye placement (Federation, 2015a).

Ranking. Ranking of sleds is determined after each heat, solely by ordering the sleds from lowest elapsed time to cover the bobsled track to highest elapsed time (Federation, 2016e). The lowest elapsed time is considered rank number one. After multiple heats, it is the sum of the elapsed time from all heats contested that determines rank, again with the lowest total elapsed time ranked as the number one sled (Federation, 2016e). Push start times are not considered for sled ranking after individual heats or in summary of competition, though there is likely a significant effect of push start time and velocity on finish time (Morlock & Zatsiorsky, 1989).

Bobsled Team Composition. In bobsled racing 2-man crews are composed of one pilot and one brakeman, while in 4-man competition, crews are composed of one pilot and three brakemen (Federation, 2016e). All athletes are required to push the sled at the start for optimal performance, and thus, all are push athletes. In general, 2-man bobsled brakemen are often selected from the crew of three brakemen that make up the 4-man crew of the same pilot, though this is not required (Federation, 2016e, 2016f). Given the inverse relationship between the body mass of the two athletes and the weight of the sled being pushed, which is essentially required by the need for momentum maintenance against energy losses throughout the race, (Braghin, Belloni, Melzi, Sabbioni, & Cheli, 2016; Itagaki, Lemieux, & Huber, 1987; Motallebi, Dabnichki, & Luck, 2004; Poirier, Lozowski, Maw, Stefanyshyn, & Thompson, 2011) larger mass of the 2-man brakeman, relative to average 4-man brakemen, may be physically advantageous, though not the primary determinant of athlete selection. This is discussed in further detail in “Other Potential Determinants of Bobsled Pushing Performance” of the present manuscript.

In 4-man bobsled, there exists a common and intuitive conception that the more powerful, slower push athlete on the 4-man crew should be the second to load into the sled behind the driver, followed by the faster athletes, with the fastest of the push athletes positioned in the true brakeman position, in the rear of the sled (Dabnichki, 2016). The intuitive rationale for this team composition organization is that the second athlete to load into the bobsled will experience lower running velocities, in accordance with his ability, and the brakeman who conventionally loads into the sled last, will be capable of withstanding the higher velocities necessary for this later-timed load (Dabnichki, 2016). This protocol is currently followed by many national bobsled federations including USABS (Association, 2017; Federation, 2016f; Skeleton, 2017; Skeleton, 2017d).

The present author posits that it could be advantageous for the second-loading side-push athlete to be the fastest push athlete of the crew, and that the true brakeman need not possess exceptional speed ability, given that the true brakeman is able to load into the sled at any time during the push without significant interference to the other athletes’ loading paradigm, due to the open back end of the sled. Given that the seating order is usually started in the rear, from brakeman to the athlete riding second, who often remains momentarily exposed to the effects of drag after loading, standing behind the driver (see Figure 2.1), this proposed team composition organization ensures that all push athletes, including the brakeman, are able to exert all their possible acceleratory impulse without delaying any portion of the team’s loading onto the sled or their seating process within it.

Figure 2.1. Seating Order in the 4-Man Bobsled Load. Adapted from: https://www.youtube.com/watch?v=_gEmWWmsXVM (fastbak1, 2010)

One of the most notable exceptions to the first conception, provided frequently in coaching and conversation by the USABS coaching staff, was the American gold medal-winning 4-man sled at the 2010 Vancouver Winter Olympic Games. In this specific case, the true brakeman in the sled routinely expressed slower sprint speeds than the average for the USA National Bobsled Team, as measured by 30m sprint times during official USABS Combines. (Skeleton, 2017a, 2017b). However, the same athlete regularly had the highest power output on the USA National Bobsled Team by nearly 10%, estimated via a one repetition maximum power clean, usually in excess of 170 kg (Skeleton, 2017a, 2017b). Indeed, with a slower more powerful athlete in the brake position on the 4-man sled, this American team's push times were tied for the second fastest at these Olympics. Perhaps more indicative of potential advantage, their start velocities were in excess of all other teams, and were faster than the next fastest sled by approximately four tenths of one kilometer per hour, on average, per heat, which is a larger than normal margin (Federation, 2016f). This is in direct opposition to convention, which states that the fastest man on the team should be in the brakeman position because they are conventionally the last man to get off the ice and into the sled (Dabnichki, 2016). One of the goals of the present study is to elucidate the interrelationship between start velocity, start time, and finish time. It is currently well accepted in the bobsled community that start velocity is approximately as important as start time in determining finish time, if not more important, (Dabnichki, 2016) and that one tenth of one kilometer per hour is a meaningful difference in velocity at the start. In any case, neither of these team composition organization rationales have been tested openly or published for public access and it appears that the conventional intuition currently reigns supreme in the sport, (Dabnichki, 2016) but this contention contrary to convention provides direction for future research once various physical characteristics of elite bobsled athletes are elucidated further.

Weather in Bobsled. It is generally accepted within the sport of bobsled that when timing and start order matter most is when inclement weather is present (Poirier, Lozowski, & Thompson, 2011). Track breakdown is subjectively noted by coaches, commentators, and athletes alike throughout training and racing heats. Ice is generally refrigerated to prevent excessive melting or sublimation, but the quality, uniformity, and hardness of the ice can all change in relation to the environment, which is one of the principal concerns of the International Olympic Committee when determining host sites (Rutty et al., 2015). Hard ice is considered faster, so long as the ice is not overly cold, such that the ice can't be sufficiently melted to form a water barrier between itself and the bobsled runners (Bowden & Hughes, 1939; Poirier, Lozowski, & Thompson, 2011). It is well-accepted that snow significantly affects race outcome due to increased friction, (Braghin et al., 2015) and measures are taken regularly throughout the race to prevent buildup of the snow within the start grooves or on the track where the runners of the bobsled usually travel (Federation, 2016e).

Apparel in Bobsled. Apparel in bobsled is generally limited to a few select items to maximize sprinting and pushing ability of the athletes through low weight-carriage and low aerodynamic resistance (Dabnichki & Avital, 2006). These items include shoes, helmet, "speed suit" as a uniform, undergarment, usually gloves and burn vest for brakemen, and optional mouth guard and socks (Federation, 2016e).

Figure 2.2. Comparison of the ground and ice contact surface and spike design of bobsled brush spikes with track and field sprint spikes.

Shoes. Shoes worn in bobsled are specific to the sliding sports of skeleton and bobsled, and are usually referred to as brush spikes (Federation, 2016e). They are similar in build to track spikes but to ensure adequate traction while sprinting on ice, rather than six to eight quarter-inch-long “pyramid” or “tiered” spikes, as is common in track and field sprint shoes, there are a minimum of 250 needles of no greater length than 5 mm and diameter of 1.5mm (Federation, 2016e). A comparison of the shoe types and their spikes used for traction are viewable in Figure 2.2.

There is a paucity of research on sprint spike design because of the proprietary nature of the manufacturing and design process within the companies, and only one study exists, to date, on the characteristics of bobsled shoes that are advantageous for push start performance (Park, Lee, Kim, Yoo, & Kim, 2015). This lone study essentially concluded that a more rigid underfoot “plate” would be advantageous as compared with more flexible alternatives (Park et al., 2015). This finding is in alignment with findings with regard to sprint performance (Smith, Lake, Sterzing, & Milani, 2016) as well as the various costs and marketing strategies and shoe descriptions of the leading sprint spike manufacturers in track and field (Eastbay, 2017). Interestingly, there is only one company currently manufacturing bobsled brush spikes. And, while many sprint spikes utilize a polyether block amide sprint “plate,” pictured in Figure 2.3, for the apparent purpose of rigidity underfoot, (Eastbay, 2017) the most common bobsled spikes appear, as pictured in Figure 2.4, to have a much more modest underfoot plate.

Figure 2.3. Lateral view of a common sprint spike design from same company responsible for primary production of brush spikes.

Figure 2.4. Lateral view of the common bobsled brush spike design.

Speed Suit. A bobsled athlete speed suit is designed as an ultra-light uniform and occasionally has a hood (Federation, 2016e). It is required by the IBSF that the material not be manufactured from a coated textile or that any aerodynamic components be added to the inside or outside of the suit (Federation, 2016e). The suit is required to cover the legs and arms, though the length of covering of the limbs is not specifically stated, which leaves room for variation in suit length across different teams (Federation, 2016e). Given the design of the speed suits are usually in the interest of reduced material for aerodynamic purposes and reduced weight-carriage by the athletes, athletes typically wear an undergarment. Comprehensive discussion of all racing apparel is warranted simply due to the constraints that it places on the total body mass allowable for the crew and the loads against which they work during the push start (J. B. Cronin & Hansen, 2005).

Helmet. Helmets with fixed full-face shields are required for all competitors in the sport of bobsled, although visors and eye protection are optional for brakemen (Federation, 2016e). All helmets used in bobsled must be commercially available in specialty shops, and not designed for the purpose of aerodynamic advantage in bobsled (Federation, 2016e). The purpose of the helmet, while patently obvious during a bobsled crash, is also conventional for protection from concussion during contact with the interior of the bobsled, though its use for this purpose is questionable, given a recent meta-analysis by Schneider and colleagues (Schneider et al., 2016). Helmet usage, including those of the full face variety, appear to principally protect against superficial head injury and reduce the incidence of skull fracture, but may or may not serve as an intervention against concussion (Schneider et al., 2016).

Mouthguard. Medical staff often recommend mouthguards as a preventive measure against concussion in sport, and many athletes wear them (Broglio et al., 2014). There appears to be strong evidence for their use in preventing dental injury, but their use in prevention of concussion is currently unwarranted according to the recent position stand published by the National Athletic Trainers' Association in United States (Broglio et al., 2014).

Burn Vest. A Kevlar burn vest is often worn by bobsled brakemen, though not required by the IBSF (Federation, 2016e). The purpose of the burn vest is to provide protection from ice burns which are caused during a bobsled crash by the heating effect of the friction of the athlete's body on the ice (Bowden & Hughes, 1939). Drivers are not known to wear burn vests, primarily because they are almost completely contained within the nose of the bobsled during travel at high speeds (Dabnichki & Avital, 2006).

Gloves. Various types of gloves from sports like football and baseball are often used by brakemen, for the dual purpose of enhanced grip on the pushing handles of the bobsled and minor protection from superficial injury within the bobsled during racing. Pilots are not known to wear gloves possibly because decreased sensitivity in their hands for the feel of the "D-rings," which are used for driving, (Federation, 2015a) could be detrimental to race performance.

<u>Awards in Bobsled Racing.</u> In bobsled racing at the North American Cup, Europe Cup, and World Cup levels, there are medals awarded for the top six fastest teams in both 2- and 4-man disciplines (Federation, 2016e). Traditionally, gold, silver and bronze are awarded to first, second, and third place, while fourth through sixth are awarded commemorative medals and are recognized with the top three teams on the podium (Federation, 2016e).

Points going towards IBSF annual rankings in 2-man, 4-man, and combined, are earned with respect to finishing place each race, and are organized descending at a progressively decreasing rate from 225 points for first place to 20 points for 30^{th} place (Federation, 2016e). Throughout the bobsled season it is these IBSF point rankings that assist in determining start order during World Cup competition, which Morlock and Zatsiorski demonstrated may have a significant and meaningful effect on finish time and race ranking (Federation, 2016e; Morlock & Zatsiorsky, 1989). At the termination of the season, the IBSF gives first, second, and third ranked teams worldwide, awards in each discipline (2- and 4-man bobsled) and the combined (Federation, 2016e).

Regulations in Bobsled

The sport of bobsled is governed by a rules book which is annually published by the International Bobsleigh and Skeleton Federation (Federation, 2016e). Within the rule book are various sections for the many portions of bobsled racing, including, but not limited to: track regulations concerning the start ramp, timing eyes and the finishing stretch; (Federation, 2015a) sled regulations concerning various aspects of the sled, like size, shape, weight, and materials used; and crew regulations concerning weight limits and apparel and safety equipment (Federation, 2015a, 2016e).

Track Regulations. Track regulations as they relate to the present study include those referring to the length and gradient of the track and its physical characteristics, as well as the start ramp and its various components (Federation, 2015a).

Length of Track and Track Characteristics. Tracks range in competition length from 1207 meters (Igls) to 1722 meters (St. Moritz) and all new tracks are to remain between 1200-1650 meters in competitive length (Federation, 2015a, 2016a). The deceleration stretch, outside of the timing zone which comprises race times, extends sufficiently that a sled can slow to a maximum of 30 km/hr without the use of brakes before colliding with a final padded braking mechanism at the end of the track (Federation, 2015a). Bends in the track generally follow the natural slope of the land, and continue downhill for 87-100% of the competitive length of each track (Federation, 2015a). The remaining portion of the competitive section of track often slopes uphill before the finish line (Federation, 2015a).

Start Ramp. The beginning of the start ramp is delineated with a start block which sits nearly two meters long, 20 cm wide, and 5 cm high (Federation, 2015a). The first timing eye is placed 15m from block and is used to measure the time of day at which the sled's nose interferes with its beam (Federation, 2015a, 2016e). The ice stretch of 15 meters between the start block and the first timing eye is sloped downward at 2% grade, and contains parallel grooves that are 8.5 mm wide internally, separated from each other by 670 mm on center (Federation, 2015a). These grooves continue through most of the remaining start ramp, but the length of their continuance is determined on a race-by-race basis by IBSF and track officials (Federation, 2016e). Beyond the 15-m line, where the first timing eye sits, there is another minimum 60-m stretch of track to allow the sled to reach an excess of 35 km/hr and the crew to load into the sled, all before reaching the first turn (Federation, 2015a). At 50 m beyond the first timing eye, there is a second timing eye, which reads the time of day to the nearest 1000^{th} of a second that the sled crosses its beam, as do all subsequent timing eyes (Federation, 2015a, 2016e). Time elapsed from one eye to the next, are calculated and truncated to the nearest 100^{th} of one second for bobsled racing (Federation, 2016e).

Sled Regulations. The sleds used in the sport of bobsled are technologically advanced because of their need for aerodynamic profiles and responsive driving performance (Berton et al., 2004; Dabnichki & Avital, 2006; Morlock & Zatsiorsky, 1989). Because of the various technological strategies possible to create a bobsled capable of carrying a pilot and crew at high speeds down the tracks, there are a litany of regulations regarding size measurements at various locations on the sled, as well as weight measurement and runner specifications that must be met (Federation, 2016e). Without meeting all of these standards put forth by the IBSF, a team will be disqualified from competition (Federation, 2016e).

Sled Size and Shape. Of the measurements made of various heights, depths, thicknesses, lengths, and widths to ensure each sled fits within the regulations, few are important for consideration for the present study. Notably, there is a standard height range of 670-870 mm for the brakeman's handles in 2-man and 4-man bobsled, as well the push bars for the side push athletes in 4-man bobsled (Federation, 2015a). Further, there is a minimum size of 20 cm long, 14 cm wide, and 5 cm thick for the bunk, on which a side-push athlete usually steps in order to load into the sled once pushing has ceased (Federation, 2015a). The remainder of sled measurements pertain little to the specific needs of the push athlete and are comprised of measurements made at common locations on all bobsleds like the axles, nose cone, bunks, upper cowling and internal frame (Federation, 2015a). Because all sleds are required to fit within these regulations, (Federation, 2015a) the specifics merit no further discussion pertaining to the present study.

Sled Weight. There are strict weight regulations in the sport of bobsled which provide a framework within which the athletes must operate, as they are a portion of the total weight (Federation, 2016e). Minimum 2-man sled weight, including runners and all components of the sled, without the crew, is 170 kg (Federation, 2016e). Minimum sled weight in 4-man bobsled is 210 kg (Federation, 2016e). The total weight of the sled with runners and crew, including all apparel and equipment for 2-man bobsled is 390 kg, and for 4-man bobsled is 630 kg (Federation, 2016e). The maximum allowable weight can be achieved by adding ballast weights secured within the sled (Federation, 2016e). This sets the regulations within which the weight of the athletes must fit.

Crew Regulations. The crew weight regulations are set effectively via the minimum empty sled weights in 2- and 4-man bobsled, in combination with the maximum crew plus sled weights. Given a minimum empty sled weight of 170 kg in 2-man bobsled and a maximum sled plus crew weight of 390 kg, the crew can weigh up to a maximum of 220 kg, including their apparel and protective equipment (Federation, 2016e). In 4-man bobsled the minimum empty sled weight of 210 kg and the maximum sled plus crew weight of 630 kg results in an effective maximum crew weight of 420 kg (Federation, 2016e).

The 220 kg 2-man crew weight limit and the 420 kg 4-man crew weight limit set the constraints for discussion of desirable size and stature of bobsled athletes. In general, athletes wear as little clothing as possible, in the form of a thin burn vest, spandex suit, any undergarments, motorcycle helmet, gloves, and brush spikes. Any aerodynamic additions to any athlete outside of stock manufactured helmets is illegal (Federation, 2016e). The weight of these all taken together is roughly 2.5-3.5 kg per athlete. This results in a maximum athlete weight, on average within a minimum weight sled, for 2-man competitors of about 107 kg per athlete, and for 4-man competitors of about 102 kg per athlete.

<u>Summary and Discussion of Post-World-War-II Race Results</u>

A comprehensive race-result history provides the framework for understanding the need for the study of the sport of bobsled outside the currently dominant countries. It is notable that the Swiss and German teams have dominated the pre- and post-World War II era of international bobsled competition (Federation, 2016b). The commonly used metrics for success in the sport, when comparing nations, are the number of total medals, number of gold medals, and occasionally a points system proposed in 1924 and though still informal in 1932 was recognized in the official report of the III Olympic Games (Lattimer, 1932). Points were awarded as shown in Table 2.2, for the top six “places of honor,” and were intended to weight a gold medal above a silver added to a bronze at the Olympics (Lattimer, 1932).

Table 2.2. Points Table for Placing at World Championship-Level Events

Place	Points
1st *	10
2nd *	5
3rd *	4
4th	3
5th	2
6th	1

***Denotes:** Places still used for points scoring informally today.
Source: Official Report: III Olympic Games: Lake Placid 1932(Lattimer, 1932)

Olympics Results. The Winter Olympics are the pinnacle of competition in the sport of bobsled. Both 2- and 4-man disciplines have been competed in every 4 years (with one 2-year gap between the 1992 and 1994 Olympics, when the Summer and Winter Olympics became offset) since 1948 (Committee, 2016). Germany has reigned supreme in total medal count, gold medal count, as well as in the points system for both 2-man and 4-man bobsled disciplines (Committee, 2016). Switzerland holds the second rank, (Committee, 2016) as is apparent with visual inspection of Figure 2.5. Data associated with Figure 2.5 is available in Table 2.3. Italy has had more Olympic 2-man bobsled success historically, while the United States is historically more successful in the 4-man discipline (Committee, 2016; Federation, 2016b). Full post-WWII Olympic medal data, color coded using gold, silver and bronze, on a year-by-year and country-by-country basis, are available in Tables 10-12 in Appendix A (Committee, 2016).

Table 2.3. Total Bobsled Medal Count Data for Medal-Winning Countries in the Olympics, World Championships, and World Cup. Colors included for congruity with Figures 2.5-2.8.

Competition Type		Legend	GER	SUI	ITA	USA	RUS	CAN	AUT	GBR	ROU	LAT	BEL	FRA	KOR	SWE	ESP
World Championship	4-Man		62	39	12	18	4	4	9	0	0	3	1	2	0	2	0
	2-Man		58	39	27	12	4	8	4	3	2	1	1	2	0	0	1
World Cup	4-Man		30	16	1	10	12	8	9	3	0	8	0	0	0	0	0
	2-Man		30	22	7	7	10	15	0	0	0	4	0	0	2	0	0
	Combined		28	19	4	12	12	15	3	2	0	4	0	0	0	0	0
Olympics	2-Man		19	14	7	3	4	2	0	1	1	0	0	0	0	0	0
	4-Man		16	12	4	8	3	2	3	1	1	1	1	1	0	0	0

Source: https://www.olympic.org/olympic-results. (Committee, 2016)

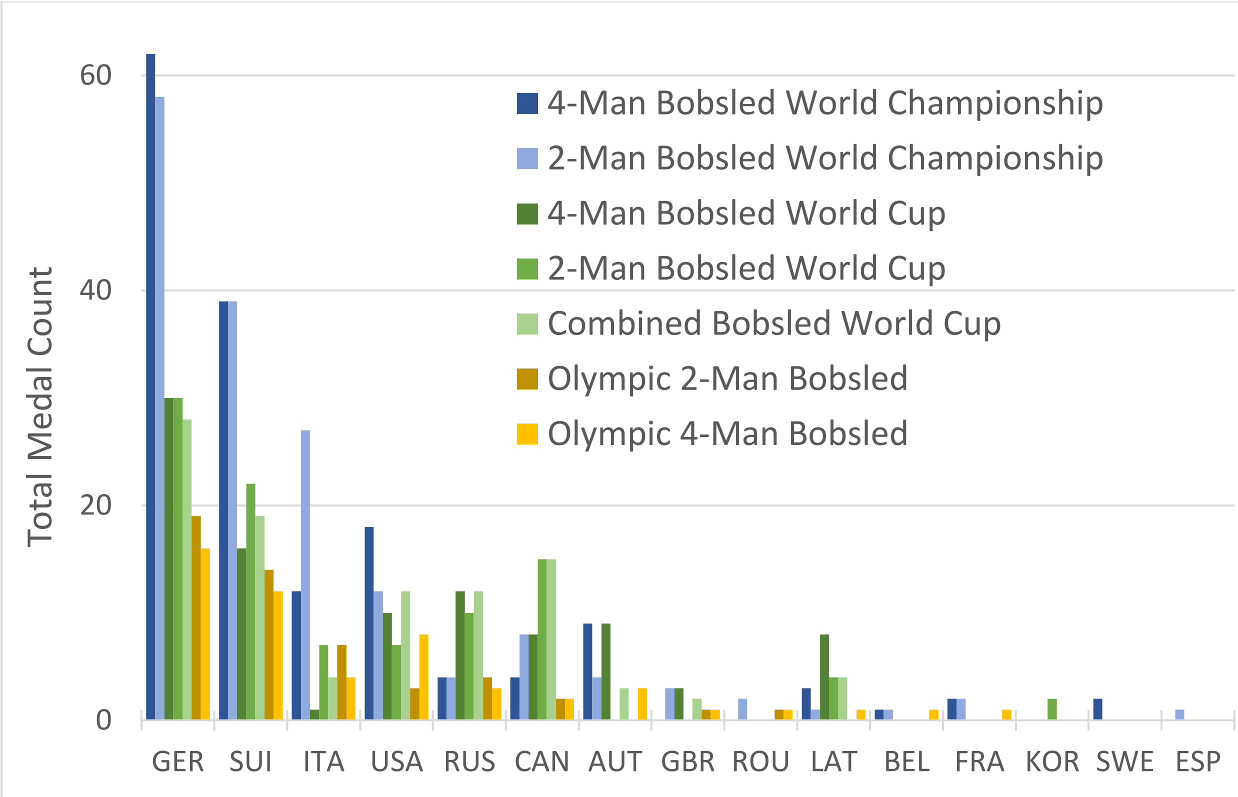

Figure 2.5. Total Bobsled Medal Count Comparison for Medal-Winning Countries in the Olympics, World Championships, and World Cup. Adapted from: (Committee, 2016; Wikipedia, 2017a, 2017b)

World Championship Results. German bobsled teams are historically the most successful at world championship races above and beyond their own Olympic and World Cup performances (Committee, 2016). Part of what may be contributing to this is the fact that teams tend to be more likely to medal at races on tracks within their own country (Bullock, Hopkins, Martin, & Marino, 2009). Specifically, 81-189% more likely, when examining Germany, Switzerland, Italy, and United States of America), (Federation, 2016f) and there have been no Winter Olympics hosted within Germany since before the 1940’s (Committee, 2016). However, 12 out of 54 (~22%) world championships since 1947 have been hosted within Germany, (Federation, 2016f) and this may have buoyed Germany’s success rate at world championships above their performance at the Olympics (Bullock et al., 2009). Similarly, the Swiss are also more successful on home ice, and, given that 15 of the last 54 (~28%) world championships have happened at St. Moritz, Switzerland, (Wikipedia, 2017b) it is likely that this partially, or even completely explains their extra success in world championship competition, above that of their Olympic success, since 1947 (Bullock et al., 2009). Italy has also experienced a similar effect, especially if the time constraints are limited to the 20th century (Federation, 2016f). From 1947 to 1999, Italy hosted 11 of the 40 bobsled world championships (~28%), (Wikipedia, 2017b) which aligns very well with their period of enhanced medal-winning, and may partially explain their relative success in world championships as compared to other international level competition (Bullock et al., 2009).

In contrast, USABS (formerly United States Bobsled and Skeleton Federation, USBSF), specifically, Lake Placid, has only hosted nine of the last 54 (17%) world championships. However, the US Bobsled National Team tends to realize a greater probability increase in medal-winning likelihood, compared to other nations' home ice advantages (Federation, 2016f). Since 1947, the US have won an average of 1.2 of the six available medals at a world championships while on home ice, whereas they only average slightly more than .4 medals per world championship when the competition is hosted in a country other than the US (Federation, 2016f). In general Germany and Switzerland perform exceptionally well in world championship competition relative to other nations, and this may be influenced in part by home ice advantage (Bullock et al., 2009; Federation, 2016f). This relationship can be visualized in Figure 2.6. Italy has a strong history in 2-man bobsled racing at world championships, while the US has a stronger 4-man bobsled world championships record.

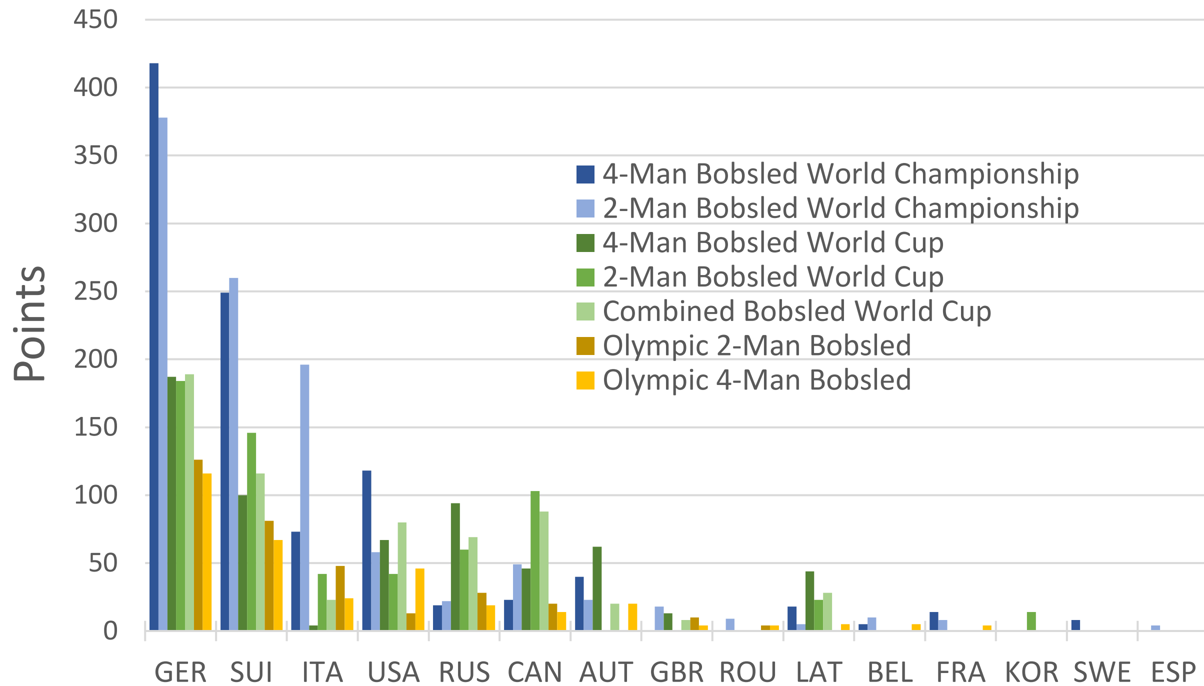

Figure 2.6. Points Totals Awarded for Top 3 Placing Across 2- and 4-Man Bobsled in the Olympics, World Championships, and World Cup. Adapted from: (Committee, 2016; Wikipedia, 2017a, 2017b)

Seasonal World Cup Results. World cup results (green bars on Figures 2.5-2.8) tend to indicate a more level playing field for more nations, because most of the time, any given nation is not performing on their home track. This can be visualized by the relatively lower percentage of medals won by, and weighted points allocated to, Germany, Switzerland, and Italy, since 1947, as compared to their success in world championship and Olympic competition (See Figures 2.7 and 2.8.).

Interestingly, countries who have hosted a relatively miniscule number of international championships tend to fair much better in earning top three rankings at the end of the season on the World Cup (Wikipedia, 2017a, 2017b). Taken together, Russia, Canada, Austria, and Latvia, have hosted a total of nine of the last 71 world championships and Olympics (~3%, per country) (Wikipedia, 2017b). This low hosting rate in combination with much higher World Cup ranking, relative to placement at championships might be indicative of a partially leveled playing field during World Cup competition (Wikipedia, 2017a).

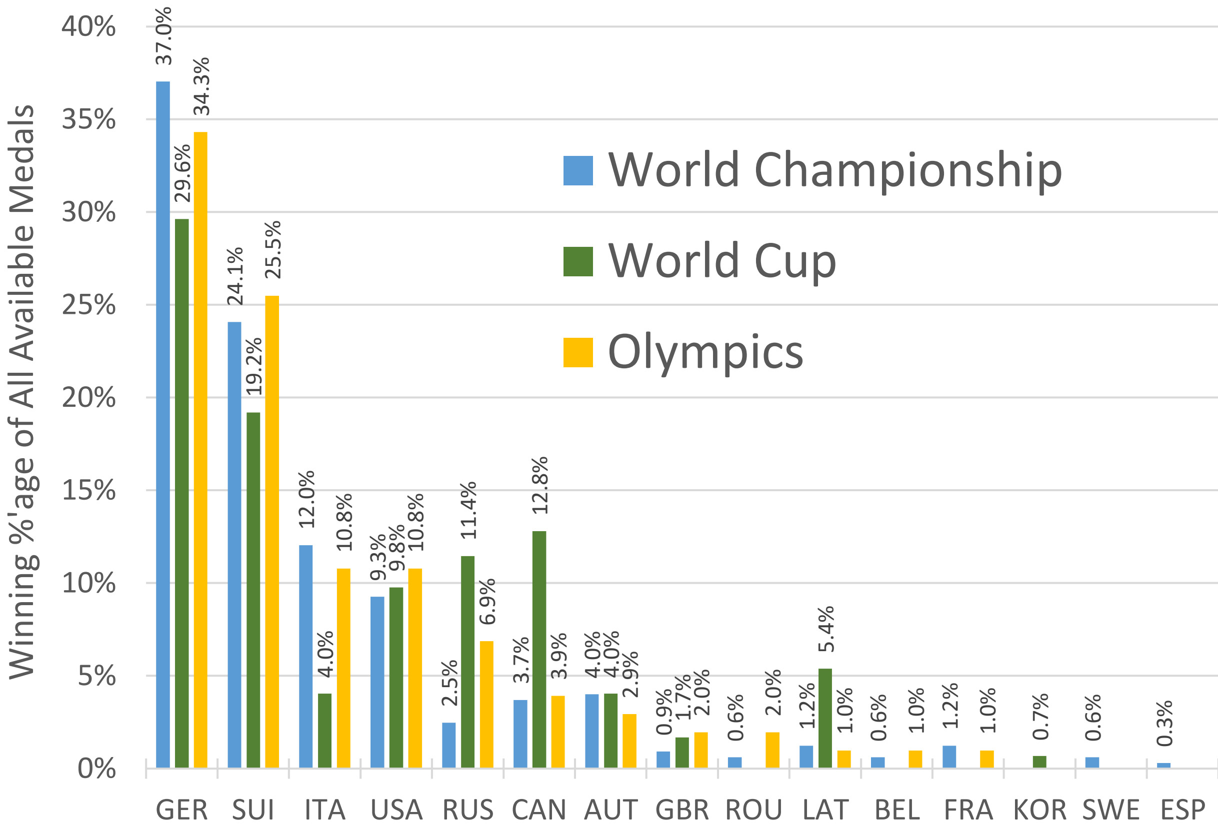

Figure 2.7. Medal-Winning, by Country, Expressed as a Percentage of the Total Number of Medals Available during the Olympics, World Championships, and World Cup Season Rankings. Adapted from: (Committee, 2016; Wikipedia, 2017a, 2017b)

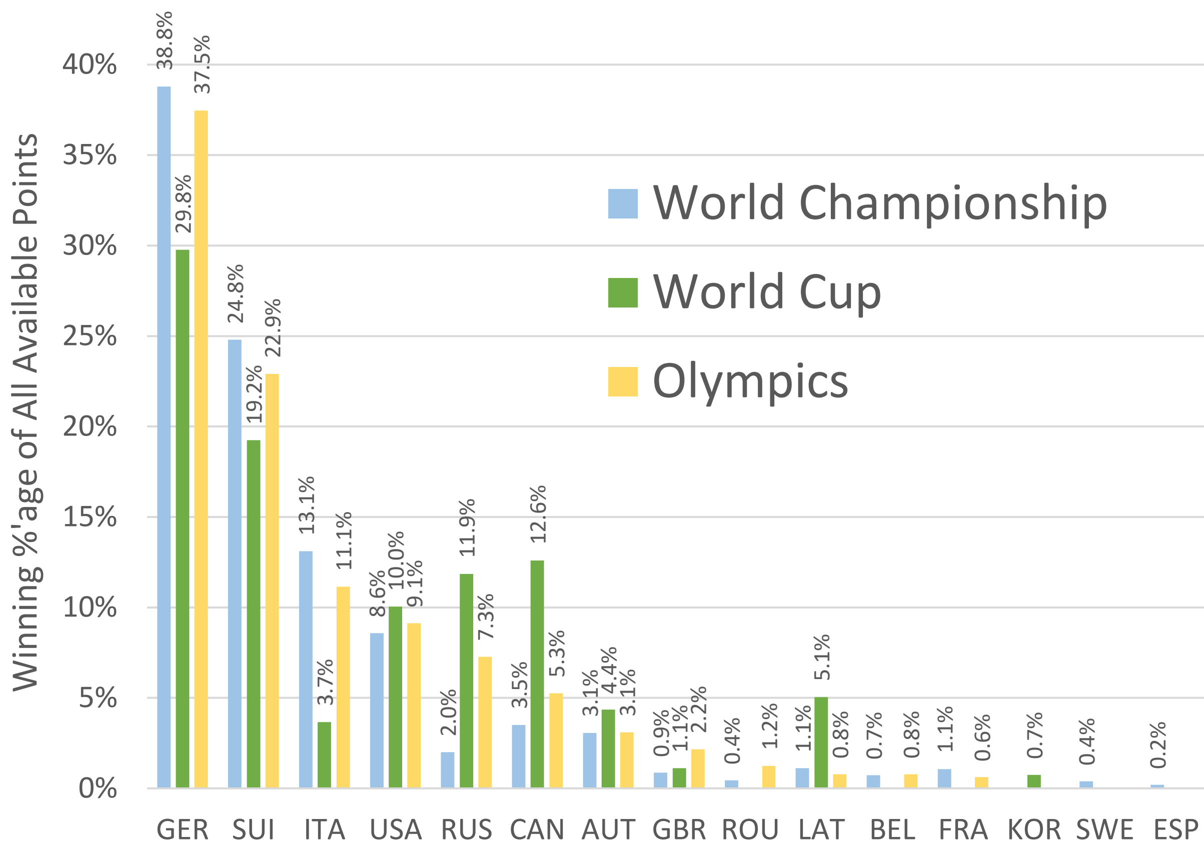

Figure 2.8. Points Allocation Based on Medal-Winning, by Country, Expressed as a Percentage of the Total Number of Points Available during the Olympics, World Championships, and World Cup Season Rankings. Adapted from: (Committee, 2016; Wikipedia, 2017a, 2017b)

Factors Affecting Bobsledding Performance

While bobsled is a conceptually simple sport, the physical complexity is extraordinary. Conceptually, the teams' intent is to push a sled with maximum effort to create momentum from the top of the track and slide to the bottom with no propulsive elements, all done as fast as possible (Federation, 2016e). This is carried out in a sequential time-trial-style race, measured to one one-hundredth of one second, usually competing against twenty or more other sleds (Federation, 2016e, 2016f). Where complexity enters the situation is in the details of the physical interaction of the athletes with the bobsled, (Brüggemann et al., 1997; Leonardi, Cecioni, Dal Monte, & Komor, 1985; Morlock & Zatsiorsky, 1989) and between the bobsled components and the icy track, (Braghin et al., 2016; Itagaki et al., 1987; Lozowski, Szilder, Maw, & Morris, 2014; Poirier, Lozowski, Maw et al., 2011; Poirier, Thompson, Lozowski, Maw, & Stefanyshyn, 2011) as well as the ambient air, (Motallebi et al., 2004) which also interacts with the crew during the race (Gibertini, Soldati, Campolo, Andreoli, & Moretti, 2010). During the push phase of the race, while athletes are still in contact with the ice via their feet, these physical interactions are all occurring, although the variability of the driver's input is momentarily not at play because the front steel runners, which can turn the sled, usually remain in the grooves throughout the pushing process. Once the athletes are no longer in contact with the ice, and are in position within the sled, only gravity will act to continue the acceleration of the sled due to the resultant normal force exerted by the track, a portion of which is in the direction of travel (Braghin et al., 2015). Given that gravity acts on all bodies in exact proportion to their mass, and mass of the system is fixed, there is no advantage to be gained in positive acceleration with respect to other teams once the athletes are within the sled and their bodies have the same velocity as the sled (MacDougal, 2012; Walker, 2010).

Thus, the race becomes a physics problem of minimizing energetic losses so that the current kinetic energy is maintained and the potential energy available, due to the height of the bobsled above the finish line altitude, can be maximally converted to kinetic energy throughout the race, resulting in the highest possible velocities and shortest time to completion (Braghin et al., 2015). Assuming normal travel down the track with no crash or overturning of the sled, the sources of possible energetic losses are as follows: runner interaction with ice, air interaction with the sled and crew, sled bumper interaction with usually-ice-covered concrete walls, (Braghin et al., 2015) as well as normal forces that are partially directed in the opposite direction of the sled's travel which will only be present in the case that the terminal portion of the bobsled track is uphill before the finish line. All of the aforementioned energetic losses along with the kinetic energy imparted to the system during the push start are cumulatively responsible for creating the total elapsed time of a bobsled run, and are thusly important considerations in the analysis of bobsled racing performance (Braghin et al., 2015).

Push Start

The push start is the only opportunity for the team of push athletes, including the pilot, to provide positive input of energy to the sled at the beginning of the race. The push start is measured in two ways and both are depicted in Figure 2.9. First, the push start time is defined as the elapsed time taken between two sequential timing eye beam-disturbances, 50 m apart, located at 15 m and 65 m from the starting block. Second, is a velocity reading usually at the end of the push ramp, near the second timing eye. This velocity measurement method is track-dependent, however, and some tracks use timing eyes that are so excessively far apart to create an estimate of velocity, that it may not be worth using that datum as a measure of purely push start performance. The details of velocity measurement will be discussed in greater detail in Chapter 3.

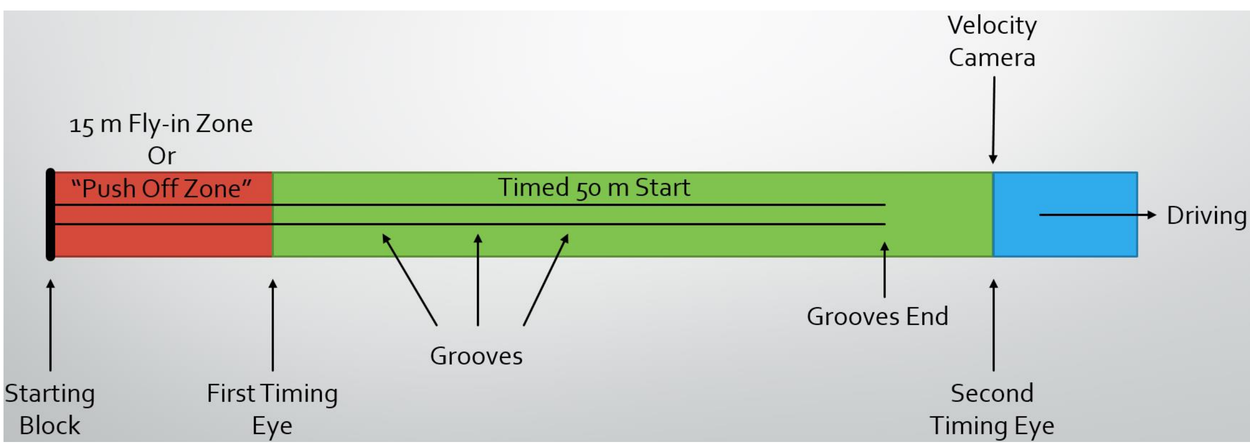

Figure 2.9. Bobsled Start Ramp Schematic. Adapted from: http://www.ibsf.org/images/documents/downloads/Rules/2016_2017/2016_International_Rules_BOBSLEIGH_AMENDED.pdf (Federation, 2016e)

Most bobsled athletes and coaches currently recognize the meaningfulness of very small amounts of time and their potential effects on race outcome, but to highlight the point further: in the 2014-2015 World Cup bobsled season, 6 out of the 18 total races (~33%) in both men's disciplines were decided by .05 seconds or less between first and second place (Federation, 2016f). In the Calgary World Cup 4-man race in 2014, there were 10 sleds within 5 tenths of each other from 3rd to 12th place, meaning that, on average, for every tenth of time lost, a crew could expect to drop two spots in the rankings in that particular race (Federation, 2016f). While these are examples of very tight temporal spacing between teams, there are a numerous more examples of very small percentage differences in performance being the difference between gold and first loser, or worse (Federation, 2016f). For example, in the 2014-15 World Cup hosted by Lake Placid, the 4-man bobsled race winner was only .04 seconds faster than the third place team, and with total times nearing 110 seconds, the percentage difference between bronze and gold was just over three hundredths of one percent (.037%) (Federation, 2016f).

On average, a 1% change in performance would have resulted in an 8-10 position swing within any given World Cup race in the 2014-15 season (Federation, 2016f). For perspective, in the 2016 Rio Olympic Games 100m final, a 1% difference in performance would have only resulted in about a 2-position change (2.07, average) for any given athlete (Committee, 2016). It is common among endurance racing sports at the championship level for the gaps between finishers to equate to miniscule percentages of total race time, as in the 2012 London Olympics men's 10000m race, where the victor was separated from the second place athlete by less than half of one second in a nearly 30 minute race (.03%) (Committee, 2016). But, in endurance sports, this is less likely to reflect indistinguishably small differences in performance capability, and rather, probably reflects racing strategy. In bobsled, the race is held in sequential time trials with no method for athletes or teams to “pace” or to be accurately aware of their elapsed time or position relative to other sleds during each of their heats, thus, greatly reducing the chance that any athlete or team is not racing at full effort or is employing racing strategy of any kind (Federation, 2016e). There are few sports that have as narrow margins of victory as men’s bobsled when this is the case (Committee, 2016).

Given the critical importance of very small amounts of time, the team of athletes should probably seek to impart as much kinetic energy to the system (athletes’ bodies and sled) and create as much velocity as possible from the top of the track to ensure the highest possible speeds throughout the run (Brüggemann et al., 1997; Dabnichki, 2016; Morlock & Zatsiorsky, 1989). It is also likely important that they cover the 50-m start zone as fast as possible because the time taken to do so contributes to the overall elapsed time (Federation, 2016e).

Table 2.4. Proportional Differences Between Time and Distance Portions of the Start Comprises in Bobsled Racing.

Bobsled Track Location	Competition Length (m)	Percentage of Competition Length Provided by 50 m Start	Portion of Elapsed Time Comprised of 50 m Start		
			% (Mean +/- SD)	Minimum %	Maximum %
Altenberg, GER	1413	3.5%	9.4% +/- .1%	9.1%	9.7%
Calgary, CAN	1494	3.3%	9.4% +/- .1%	9.2%	9.7%
Igls, AUT	1207	4.1%	9.9% +/- .1%	9.7%	10.1%
Konigssee, GER	1251	4.0%	9.8% +/- .1%	9.6%	10.1%
La Plagne, FRA	1508	3.3%	10.1% +/- .2%	9.7%	10.4%
Lake Placid, USA	1455	3.4%	9.2% +/- .2%	9.1%	9.5%
Park City, USA	1335	3.7%	Not Contested in 2014-15 World Cup		
Pyeongchang, KOR	1376	3.6%	Not Yet Contested		
Sochi, RUS	1500	3.3%	8.7% +/- .1%	8.4%	9.0%
St. Moritz, SUI	1722	2.9%	7.7% +/- .1%	7.5%	8.0%
Whistler, CAN	1450	3.4%	Not Contested in 2014-15 World Cup		
Winterberg, GER	1330	3.8%	Not Contested in 2014-15 World Cup		

Adapted from: http://www.ibsf.org/en/tracks. (Federation, 2016a) And from: http://www.ibsf.org/en/races-results. (Federation, 2016f)

While the 50-m long portion of the track only comprises 2.9-4.1% of the physical length of the timed portion of the tracks, the same start phase comprises 7.5-10.4% of the elapsed time taken to travel the length of the competitive portion of the tracks (Federation, 2016a). See Table 2.4 for track-specific descriptive data with regard to the portion of the total elapsed time that is taken to complete the 50-m start. The average proportions for all tracks on which World Cup competition took place in the 2014-15 season is summarily presented in Figure 2.10. The present study discusses the statistical relationship of start times to finish times in much greater detail in Chapter 3.

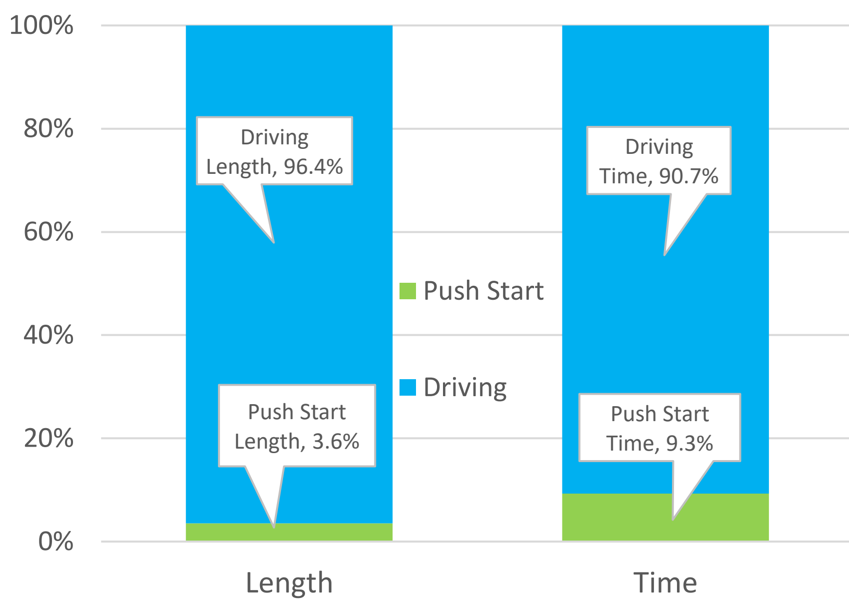

Figure 2.10. Graphical Representation of the Average World Cup Bobsled Proportion of the Track Length and Elapsed Time that is Comprised of the Push Start. Data adapted from: http://www.ibsf.org/en/tracks. (Federation, 2016a) And from: http://www.ibsf.org/en/races-results. (Federation, 2016f)

The momentum that is imparted through work done, or net impulse applied by the athletes along with the slope of the track at the start, will be carried with the sled into the driving portion of the track, (Dabnichki, 2016; Morlock & Zatsiorsky, 1989) and will be subject to all the energetic losses that will be discussed in the immediately following section (Braghin et al., 2015; MacDougal, 2012). It is possible that the added momentum provided by the athletes at the start could remain advantageous in instantaneous velocity measurements all the way to the finish line but there have been limited studies to examine any carryover and the magnitude of the relationship between start time and velocity with finish times (Morlock & Zatsiorsky, 1989). The relationship between start velocity and finish time is explored in detail in Chapter 3 of this manuscript.

Energetic Losses

The three principal physical categories of energetic losses during the sliding of a bobsled on an ice-covered bobsled track are drag from the air, surface friction, and any normal forces in the opposite direction to travel (Braghin et al., 2015; MacDougal, 2012).

Drag. Aerodynamic drag, or simply, drag, is a type of friction that is exerted on an object moving through a fluid or gas, and is exerted, like friction between surfaces, as force in the parallel and opposite direction of motion (Merriam-Webster, 2017; Walker, 2010). Unlike friction between surfaces, drag increases proportionately with square of velocity (Walker, 2010). This relationship is especially important because drag forces become quite substantial (upwards of 100N) (Gibertini et al., 2010) in the range of maximum velocities experienced by the sled and crew (130-155km/hour, depending on track, discipline, and performance level of team) (Berton et al., 2004; Federation, 2016c; Gibertini et al., 2010).

Several studies have examined the benefits of aerodynamic modifications of bobsleds and their crews' riding positions and team composition, (Dabnichki & Avital, 2006; Gibertini et al., 2010; Lewis, 2006; Motallebi et al., 2004) and it is common for nations to privately seek wind tunnel testing with their highest-level bobsled crews and sleds (Berton et al., 2004; Gibertini et al., 2010). One such study on the French National Bobsled Team examined the effects of various aerodynamic additions to the 4-man bobsled, along with an optimization of the riding position and team composition (Berton et al., 2004). Using a step-by-step analysis of, first, testing for team order effects on the drag coefficient, then adding and testing aerodynamic additions to the exterior of the sled, and finally optimizing the riding position of the brakeman, the researchers and French athletes were able cause a reduction in drag coefficient from about .250 to values in the range of .234-.237 (Berton et al., 2004). The research team hypothesized that this could result in a gain of 5km/hr at maximum speed, but this was proposed with only aerodynamic limitations in mind (Berton et al., 2004). Simply creating the same force of drag at new, higher speeds in a lab-tested environment may not result in such a substantially increased performance on a bobsled track because of the limited time available for the sled to attain that speed, and because with increased speed the difficulty of navigating the track may increase. Further, increased speed will cause greater friction between runners and ice under the pressure of turns due to the increased normal force (Poirier, Lozowski, Maw et al., 2011). Thus, while meaningful, it is possible that the researchers overstated the actual time-effects of the decreases in drag coefficient caused by modifications to sled and crew.

Other aerodynamic analyses and optimizations of bobsled builds have also resulted in significant reductions in drag coefficients, and thus, drag force at given velocities (Gibertini et al., 2010). Gibertini et al. (2010) were able decrease drag force by 8.9% during a 140-km/hr wind tunnel test by making a nose cone shape change and by raising the bobsled 2 cm higher from the ice to allow more laminar flow to occur around and under the bobsled cowling. Notably, when crew and runners are present during wind tunnel tests at 140km/hr the drag force was calculated at 137 N. Using the impulse-momentum relationship, and given a maximum-weight 2-man bobsled of 390 kg, this drag force would result in an acceleration in the opposite direction of travel of 1.26 km/hr/s. That is, the bobsled would be slowed by drag alone on a flat portion of the track by 1.26 km/hr in one second from 140 km/hr to ~138.7 km/hr. A reduction of drag force by 8.9% to get to the reported, reduced drag force of 137 N, means that the original sled build was resulting in slightly more than 150 N of drag force at 140 km/hr. This would have caused a negative acceleration of 1.39 km/hr/s resulting in a loss of 1 km/hr *more* than the optimized build over the course of approximately 8 seconds, due to drag force-related energy losses alone.

Given that more than half of the race on most tracks will be spent traveling between 110-140km/hr, (Federation, 2016f) and an average half-heat duration was 28.0 seconds for all tracks in 2014-15 World Cup competition, (Federation, 2016f) if we assume an average velocity of 125 km/hr for the second half of the track, calculating a conservative estimate the time gained in the optimized build versus the original due to the drag force is relatively simple. Drag force at 125 km/hr would be roughly 92 N for the non-optimized build and 84.5 N for the optimized build, given the relationship between the square of velocity and the drag force. Spending 28 seconds traveling with a difference of 7.5 N drag force, on average, using the impulse momentum relationship, would result in a predicted difference in speed of .53 m/s or 1.9 km/hr at the end of the 28 seconds. So, on average, for the original non-optimized sled during that time of negative acceleration relative to the optimized sled, the average difference in velocity would be ~.95km/hr (half of 1.9 km/hr), putting the optimized sled about 7.4 m behind the original at the finish line, when only considering the temporal second half of the race. When traveling ~130 km/hr, as is common to sleds nearing the finish line, (Federation, 2016f) 7.4 m equates to a time difference of two tenths of one second, if the marginal speed increases exhibited by the aerodynamically optimized sled didn't cause increased energetic losses due to friction during the 28 seconds of travel. There are no studies to date that have examined the effects of a drag optimization on resultant increases in friction due to the increased normal forces that comes with increased velocity during turns. The present authors contention that the French sled-optimization study overstated the benefit of drag is supported by the much more modest improvement in performance likely to be achieved by the Italian sled-optimization process, given that reported drag coefficients in both studies were comparable (~.250) (Berton et al., 2004; Gibertini et al., 2010).

Friction. Friction is defined as a force acting directly in opposition to the motion of two surfaces moving in contact with each other, due to their interaction, and is directly proportional to the normal forces exchanged by the two surfaces and the coefficient of friction created by the nature of the surfaces (Walker, 2010). A recent study also detailed a “plowing” force (Lozowski, Szilder, & Poirier, 2014) which can best be visualized in Figure 2.11.

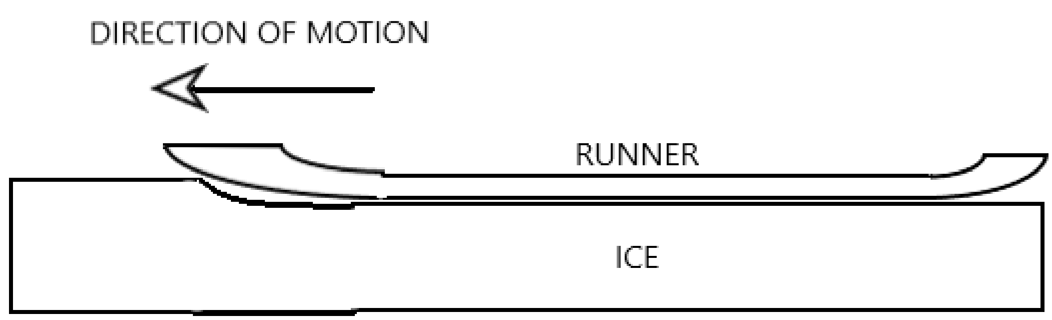

Figure 2.11. Visualization of the plowing force at the front end of the bobsled runner as it moves through the top layer of the ice.

In the case of bobsled, another subtype of friction, lubricated friction, is likely also at play (Bowden & Hughes, 1939). Because of the occasional difference between runner temperature and the ice surface temperature, it is possible that that simply the difference in temperature causes melting of the surface of the ice to occur, creating a lubricated friction scenario (Federation, 2016e). Further, when two surfaces rub together kinetic energy is converted to thermal energy which could enhance the heating and melting of the surface of the ice (Walker, 2010). Thus, the IBSF places strict constraints on runner temperature during training and racing, so as not to allow hot runners sliding rapidly over the ice to be used as a performance enhancement technique and to prevent excessive ice deterioration on the bobsled track (Federation, 2016e).

Within those guidelines regarding runner temperature immediately before racing is a threshold of up to 4° C (Federation, 2016e). That is, the race runners at the time of their use in the race heat, can exceed the reference runner by up to 4° C without incurring penalty (Federation, 2016e). Interestingly, in 1987, there was a somewhat simple and flawed study that was still able to show meaningful differences in the coefficient of friction of polished bobsled runners at varying temperatures, including with differences as small as 4° C (Itagaki et al., 1987). It is also well established that variations in ice temperature have a meaningful effect on the coefficient of friction between ice and bobsled runners (Lozowski, Szilder, & Poirier, 2014; Poirier, Lozowski, & Thompson, 2011).

The primary source of surface or lubricated friction in the sport of bobsled is the runners in contact with the ice due to the normal force constantly applied and the long duration of friction force application (Braghin et al., 2016). And, while the study by Itagaki et al. (1987) examined various runner materials and degrees of hardness, in 2006, the FIBT, now the IBSF, put into place a rule to standardize all runner steel in the sport of bobsled (Federation, 2016e). Thus, a nearly 20% change in coefficient of friction due to temperature variation within the legal limit set by the IBSF could provide the primary means of friction reduction, (Itagaki et al., 1987) if all teams are assumed to polish their runners equivalently, and are not allowed to apply any hardening treatments (Federation, 2016e).

To provide reference for the magnitude of the absolute frictional force that results from the interaction between runner and ice that is comparable to the drag force from the previous section of the manuscript, use of the coefficient of friction along with the normal force to calculate the force of kinetic friction is possible (Braghin et al., 2015). Several studies have examined the coefficient of friction between runners and ice and most agree that it is in the range of .004 to .006 during normal training and competition conditions (Braghin et al., 2016; Itagaki et al., 1987; Lozowski, Szilder, & Poirier, 2014). It is also well-established that bobsleds and crews can momentarily experience “G-Forces” in the range of 4.0-5.0 during high velocity turns (Federation, 2016e). Given a 2-man bobsled and crew weight identical to the previous example, (390 kg) and a normal force five times that created alone by the mass of the bobsled on a flat surface, as could be the case in a turn, (Federation, 2016e) the frictional force, not including plowing, could be around 95 N. Lozowski and colleagues (2014) suggested that at a g-force of 5.0 the plowing force of the runners could be responsible for up to 33% of the total force of friction applied. It is this plowing force of the runners that the athletes are likely modifying when they interchange between wider- and narrower-radius runners between training sessions to try to find a balance of velocity and control (Lozowski, Szilder, & Poirier, 2014). The effects of the pilot’s actions on friction will be discussed in a subsequent subsection of the “Factors Affecting Bobsledding Performance” section of the present chapter.

To the author’s knowledge, USABS does not employ any formal heating of runners nor are their cooling curve references available for athletes and coaches. Most of the variables discussed in this section about friction are less modifiable than the temperature of the runners.

And, the benefit of increased ice melting due to increased temperature appears meaningful to performance outcomes (Itagaki et al., 1987; Lozowski, Szilder, & Poirier, 2014). It is proposed that cooling curves of runners should be an area of future research because of the potential to dramatically reduce frictional forces. Lozowski and colleagues (2014) demonstrated very low coefficients of friction ($\mu < .002$) between runner and ice when ice was very near the melting point (0° C) and velocities were under 10 m/s as is the case for most of the start phase. The advantage this could provide by heating the ice more effectively during the start phase, where lower absolute sled velocities are present (Federation, 2016f) could be quite meaningful because the coefficient of friction can be as low as half ($\mu = .0025$, -5° C ice, <7.5 m/s sled velocity) of what might be considered normal for competition ($\mu = .005$ at -5° C ice, >25m/s sled velocity) (Lozowski, Szilder, & Poirier, 2014). Even if the runners do conduct any excess heat into the ice within the first 10% of the track, the advantage of a reduction of the coefficient of friction could result in a measurable start difference. At the very least, having cooling curves of runners at the ready so that if the reference runner is much warmer than the race runners for the day, the runners could at least be safely heated to the extent that they match or slightly exceed the temperature of the reference runner before being placed on the ice for competition.

Sled and Crew Total Mass

The IBSF recognizes that increasing the mass of the sleds beyond certain maximums they have set forth within their annual rules publications could be advantageous, and as such, will disqualify teams who have a post-heat “weigh-in” of even .1 kg more than the respective maximums for the various disciplines (Federation, 2016e). Table 2.5 presents the men’s sled and crew minima and maxima. However, there are no minimum standards for total sled plus crew mass; only the minimum empty sled weight to prevent excessive technological advancement necessary to continue to produce continuously lighter sleds which might be advantageous to a point, given that athletes tend to move lighter masses with greater velocity (Federation, 2016e; Haun, 2015; Hoffman Jr., 2014; Kraska, 2008).

Table 2.5. Sled and Crew Mass Restrictions (kg).

	Empty Sled Minimum	Sled + Crew Maximum
2-Man Bobsled	170	390
4-Man Bobsled	210	630

Adapted from: 2016 IBSF Bobsled Rules. (Federation, 2016e)

To the author's knowledge, there have been no studies or mathematical models to date that have looked at the magnitude of effect between incremental increases in total sled plus crew mass. Currently, there are studies about the relationship between athlete characteristics, such as mass, and competitive success in skeleton, but the quality of the study has been poor, as discussed in the in the following section (Push Effects on Split and Finish Times in Sliding Sports) of the present literature review (Larman et al., 2008). In a study of the 1994 Winter Olympics in Lillehammer, investigators identified that acceleration during a straight stretch of track in 4-man bobsled was significantly greater ($p < .05$) than in 2-man bobsled, and they hypothesized that this effect was because drag coefficients for 2-man and 4-man bobsled are not as discrepant as total mass, thus, providing an increased ratio of acceleratory normal force due to gravity to drag (Brüggemann et al., 1997). Incremental increases in weight have yet to be examined for their incremental effect on increased velocity and improved finish times.

Mass Effects Algorithm. The author of the present literature review proposes a conceptually simple algorithm as a practical means for future sport scientists to estimate the effects of incremental mass changes in bobsled. Using known energetic losses, and the ability to estimate the proportion of those losses that fall into either drag or frictional losses as a category using values in the literature, one can estimate the differential effects of system mass on finish time.

1. Acquire an estimated sled velocity profile of a desired bobsled track. Simple profiles are available from the IBSF website races results page (Federation, 2016f).
2. Subtract the altitude at the finish line from the altitude at the 65-m timing eye, which will provide the "riding altitude."
3. Using the following equation for potential energy to calculate the magnitude of energy available from the end of the push start to the finish line, which will become the "riding potential energy:"

$$PE = mgh;$$

"PE" is potential energy (J), "m" is mass (kg) of the sled and crew, "g" is the acceleration (m/s^2) due to gravity, and "h" is the "riding altitude" (m).

4. Using the following kinetic energy formula, calculate the energy of the sled and crew at the 65-m timing eye (assumed velocity measurement point) as well as at the finish line.

$$KE_a = (1/2)(mv^2)$$

"KE_a" is actual kinetic energy (J), "m" is mass (kg) of the sled and crew, "v" is velocity (m/s) of the sled and crew.

5. To calculate total energetic losses during the portion of the race after the 65-m timing eye, subtract *actual* KE at the finish from the sum of the initial PE and KE in steps 3 and 4, respectively.
6. Using the constant .0906, which is the product of mass density of air, the reference area of the bobsled, and the drag coefficient of an improved Italian 2-man bobsled

studied by Gibertini and colleagues(Gibertini et al., 2010) OR using a nations proprietary data, and the velocity profile of the track in question, calculate estimated energetic losses due to drag using the following equation for work. For this calculation, as with any integration problem, the more numerous the instantaneous measurement of velocity, the more accurate the calculations will be.

$$W = Fd$$

"W" is work (J), "F" is the drag force (N), "d" is distance traveled

7. Calculate all energetic losses that must be due to friction, by subtracting estimated energy losses due to drag from total energy losses calculated in step 5.
8. Assume energetic losses due to drag are unchanged for incremental increases in mass, given that the mass is contained within the sled, and calculate kinetic energy present at the finish line based on the increased frictional energy losses for a 1 kg addition of weight to the sled using the following formula.

$$KE_{a1} = [(m + 1)(gh) + KE_a] – E_f - (E_f / m) – E_d$$

"KE_{a1}" is kinetic energy (J) of a sled with 1 kg mass added internally, "m" is the original mass (kg) of the crew and sled, "g" is the acceleration (Nm/s^2) due to gravity, "h" is the "riding altitude" (m), "KE_a" is the kinetic energy (J) calculated from the velocity of the sled at the original weight assuming that equivalent kinetic energy (proportionately less velocity and more mass) will be produced during the push phase, "E_f" is the energy lost due to friction from step 7, "E_d" is the energy lost due to drag from step 6.

9. Using the slightly increased kinetic energy of the marginally heavier sled that was calculated in step 8, calculate resultant average velocity of the sled using the following rearrangement of the formula from step 4.

$$v_{avg} = [(2 * KE_{a1} / (m_1))^{1/2} + v_i] / 2$$

"v_{avg}" is average velocity after the 65-m line, "KE_{a1}" is the kinetic energy of a sled with 1 kg added, "m_1" is mass of sled and crew with 1 kg added, "v_i" is start velocity.

10. Using average velocity calculate elapsed time difference at the finish line by calculating the inverse of each of the velocities from before and after the theoretical 1 kg addition, to put units of velocity in seconds per meter.
11. Then, multiply the difference between the two velocities (s/m) by the length (m) of the track between the end of the start zone and the finish line.

Interestingly, carrying out the calculations exactly as described above, using data from the 1988 Calgary Olympics found by Morlock et al. (1989) and from the 2-man bobsled aerodynamics study by Gibertini et al. (2010) only slightly overestimates the actual finish time differences between 4-man and 2-man bobsled that would be expected purely because of the weight difference between the two disciplines (.0036 per kg actual, (Federation, 2016f) vs. .0045 per kg predicted using the outlined algorithm, ~20.6% difference) with unchanged drag coefficients. Bruggemann and colleagues (1997) concur that the acceleration of a 4-man bobsled relative to its mass will be slightly inferior to the 2-man sleds (~7% difference, relative to mass) because of a slightly less aerodynamic profile of the crew. Bruggeman, Morlock and Zatsiorsky (1997) also suggested that the difference in drag between bobsled teams was limited in both 2-man and 4-man, increasing the potential utility of the described algorithm because of the ability to use drag data already available in the scientific literature. Currently, it is common for athletes to unscientifically experiment with different system weights in search of an elusive advantage. Thus, it appears the present model may warrant empirical or mathematical modeling investigation as a means of gauging the importance of bobsled and crew total weight and ensuring that athletes aren't unnecessarily putting themselves at a disadvantage by racing with an underweight sled.

Driving

Another cause of increased friction between surfaces of the bobsled and the track, thereby resulting in energy losses, is the act of, and quality of, driving or steering by the bobsled pilot. All studies that have been discussed regarding the friction of runners with ice have been an examination of the friction between the runners during their straight-line travel. In straight-line examinations, the same locations of ice are first warmed and lubricated by the front portion of the runner and thus the front-most area of the runner is the only portion that experiences any non-lubricated friction (Braghin et al., 2016; Itagaki et al., 1987; Lozowski, Szilder, & Poirier, 2014; Poirier, Lozowski, Maw et al., 2011). This is not the case as a runner moves laterally on the ice when the driver is steering. Further, in straight-line travel, the front portion of the runner is exclusively responsible for creating the plowing force as the runner compresses the ice (Lozowski, Szilder, & Poirier, 2014). During a turn when the runner is translating to some degree sideways over the ice as it travels forward with the sled, as happens during "steers" made by the bobsled pilot, the plowing force must be created all along the length of the runner that is in contact with ice, greatly increasing the amount of ice that is plowed through (Lozowski, Szilder, & Poirier, 2014). This plowing force increase is probably large in magnitude and, practically, it is understood by pilots and coaches that that the less one steers, the less total interaction with the ice the runners will have.

Driving quality with regard to driving optimal lines through curves creating the greatest velocities upon exit is also considered of principal importance in sliding sports (Colyer, 2015;

Roberts, 2013). There have been no published studies on the magnitude of effect of various durations of steers, turns, or interactions between these driving characteristics, largely because of the inability to eliminate the effects of other confounding variables.

Other than runner to ice contact and the frictional interactions present because of athlete driving, there are other portions of the sled that can hit the side walls of the track (Federation, 2016e). Usually these side walls of the track are covered with ice (Federation, 2016e). It is common for portions of the track where the "optimal" line requires pilots to contact the wall, (Roberts, 2013) for the ice to have been deteriorated to the extent that the underlying concrete is exposed. The coefficient of friction between the surface of the bumpers of the sled and ice, and the coefficient of friction between the surface of the bumpers and concrete have not been analyzed to date. However, given that the duration of the contact is often quite short, and gravitational forces are not involved in adding to the normal forces in the "wall tap" scenario, it seems likely that the contribution to energy loss due to wall taps throughout the driving of the bobsled track is much smaller than runner-ice interaction or air-sled and air-crew interaction. This is an area where mathematical modeling might prove useful.

<u>Start Order</u>

Since the landmark study of the Calgary Olympics in 1988, it has been taken as fact that start order can dramatically affect the outcome of a race (Morlock & Zatsiorsky, 1989). The IBSF has since made rule adjustments to allow for the re-ordering of sleds within and between races to ensure that those who are ranked lower have an equitable chance at success within races and throughout the World Cup season (Federation, 2016e). The IBSF also rewards teams possessing higher rankings with earlier draws for start order at the World Championships and Olympics (Federation, 2016e). Specifically, the factors affecting the sleds later in the order are both physical deterioration of the ice via cracking, and also softening due to temperature changes from the friction caused by earlier sleds (Poirier, Lozowski, & Thompson, 2011). Softer, damaged ice will cause more plowing forces between runners and ice resulting in greater energetic losses throughout the run for sleds later in the start order (Lozowski, Szilder, & Poirier, 2014).

Push Start Effects in Sliding Sports: Velocities, Split, and Finish Times

Since the 1950's the use of athletes from other sports, and now athletes who train full-time as push athletes, has been common to sliding sports because of the intuitive physical understanding that the start may be important in determining the outcome of races (Federation, 2016b). The details of this relationship remain relatively uninvestigated even though ample data is publicly available for all currently operable tracks (Federation, 2016f). To date, only six studies currently published in English have been carried out on the relationship between start characteristics and subsequent velocities, split times or finish times in the sliding sports (Brüggemann et al., 1997; Bullock et al., 2009; Bullock et al., 2008; Fedotova, 2010; Morlock & Zatsiorsky, 1989; Zanoletti et al., 2006).

Of the numerous interrelationships between start characteristics and other subsequently measured variables down the track, some of the most commonly discussed are start time, (Brüggemann et al., 1997; Bullock et al., 2009; Bullock et al., 2008; Fedotova, 2010; Morlock & Zatsiorsky, 1989; Zanoletti et al., 2006) start velocity, (Brüggemann et al., 1997; Bullock et al., 2008; Morlock & Zatsiorsky, 1989) various down-track instantaneous velocities (Morlock & Zatsiorsky, 1989) and split times, (Brüggemann et al., 1997; Bullock et al., 2009; Fedotova, 2010; Morlock & Zatsiorsky, 1989) and finish time (Brüggemann et al., 1997; Bullock et al., 2009; Bullock et al., 2008; Fedotova, 2010; Morlock & Zatsiorsky, 1989; Zanoletti et al., 2006). Of these listed, only start time is measured in a completely standardized manner in terms of distance and method of measurement, however, even start times are idiosyncratic with respect to track because of the various vertical profiles of the start ramp beyond the first timing eye (Federation, 2016a). For a detailed schematic of the start ramp in birds'-eye-view, please refer to Figure 2.9 in the section titled: Factors Affecting Bobsledding Performance, subsection Push Start, within the present literature review. Start velocity is generally assumed to be measured at the instant start time is taken, and with the recent advent of intra-bobsled accelerometry being used for television purposes, this may become a more standardized method of velocity-reporting once reliability and validity are established. However, for the 2014-15 and 2015-16 seasons, accelerometry was not used in the reporting, and thus, the method of the measurement of velocity was variable from track to track (Federation, 2016f). Start velocity is also likely to be closely related to start time, given reasonable measurement of the two variables, simply because velocity is measured near the end of the 65m start phase where variability in performance is relatively low and ability to create a fast push time is nearly impossible without also creating relatively high velocities (Brüggemann et al., 1997; Morlock & Zatsiorsky, 1989). Interestingly, this relationship has never been directly studied in bobsled, though a related experiment comparing start time to velocity at 45 m from the block using skeleton athletes found strong correlations in Lake Placid, Sigulda, and St. Moritz (r = -.77, -.77, -.90, respectively) (Bullock et al., 2008). Further, all split times, velocities, and finish times are dependent on the tracks' individual placement of timing eye's and their respective competition lengths, as well as the method used to collect velocity, be it timing eye pairs placed in close proximity for instantaneous velocity estimates, or average velocity measurement between two timing eye pairs used for a split time (Brüggemann et al., 1997; Morlock & Zatsiorsky, 1989). The differences in measurement from track to track make application of currently available publications to other tracks more tenuous.

Reliability of Sliding Sport Results

In 2009, Bullock et al. compiled and analyzed, inter-race, inter-run, inter-season, and inter-track reliability for all BMW IBSF Skeleton World Cup race data from 2002 to 2006. Only three races were omitted for the four-year period of analysis. Wisely, athletes were split into top 10 and bottom half of the top 20 groups for all analyses, which presumably eliminated the effect of a meaningless strong correlation being presented because of widely disparate skill levels in niche sports like the three sliding sports. Bullock and colleagues (2009) collected ratings of difficulty for each skeleton track from Olympic coaches and athletes on a scale of 1-4 with 1 being a "pure push track" and 4 being a "pure driving track." As was predicted, the more technically-rated tracks (Torino, Altenberg, and Sigulda) exhibited the highest within-athlete coefficients of variation (CV) between runs at a given track, especially within the top 10 men (CV = .53, .59, .43%, respectively) and women (CV = .52, .89, .42%), as compared to the lowest difficulty tracks, Igls and Winterberg which had CV's, in both the top 10 men and women, near half of the more technical tracks (CV = .28, .19%, respectively for top 10 men, CV = .27, .27% respectively for top 10 women). The similarity between finish times any given year on one track and finish times on the same track in a subsequent year was relatively low compared to intra-race reliability, though overall, still quite tightly spaced given CV values ranging from .59 to .90% among all classes of World Cup level athletes. This reliability provided the basis for the examination of the overall relationship between start time and finish time that will be discussed in the following section.

Push Start Time and Velocity Relationship to Subsequent Split Times and Finish Time

Push start time is the most common variable examined when analysis of sliding sport performance is carried out, probably because it is now made readily available online and has been accessible from the IBSF, formerly the FIBT, since at least the 1980's (Morlock & Zatsiorsky, 1989). Of the six studies that examine any part of sliding performance during various races, only four studied the interrelationship between start time and subsequent split times in the sliding sports, (Brüggemann et al., 1997; Bullock et al., 2009; Fedotova, 2010; Morlock & Zatsiorsky, 1989) and only one discussed these relationships in depth in bobsled (Morlock & Zatsiorsky, 1989).

Luge. Arguably the most dissimilar sliding sport to bobsled is luge. The start in luge is begun in a seated position and the early acceleration is accomplished by a paddling action with the upper extremities. Nonetheless, because courses are nearly identical across world level luge and bobsled competition, and the races are conceptually similar, both being comprised of a start phase where the athlete adds to the kinetic energy of the system actively, then transitions into a loss-minimization process as they navigate the complex track, the luge start and its relationship to split times down-track may shed light on the analogous relationships in bobsledding.

One of the primary differences between the luge start and the bobsled start is the length (Fedotova, 2010). Time measurement for luge starts 5-10 m from the handles, as opposed to 15 m from the start block in bobsled (Fedotova, 2010). Fedotova (2010) also demonstrated that the proportion of the race that the luge start represented in absolute time was much smaller than bobsled (3-7% vs. 7.5-10.4%) (Fedotova, 2010). World Cup and world championship level athletes competing in Lake Placid still exhibited trivial to weak statistically significant correlations ($r = .26$ and $.30$, respectively, $p < .05$) between start time and finish time, even when the start time was subtracted from the finish time to create independent data series for correlational analysis (Fedotova, 2010). In Whistler, World Cup competitors in luge showed a .46 correlation ($p < .05$) between start time and finish time (Fedotova, 2010). This disparity in correlation between the two tracks is in alignment with a rating of track driving difficulty acquired by Bullock and colleagues from Olympic level athletes and coaches. It is common for more technical tracks to present lower relationships between start time and finish time (Bullock et al., 2009).

In Bruggemann and colleagues' (1997) examination of the luge event at the 1994 Winter Olympics in Lillehammer a much higher percentage of the variability in subsequent split times and finish time was predicted by the start than in Fetodova's (2010) research, but this was more likely to do with the sample size and the wide variance in ability present in the top 30 athletes at the Olympics, as opposed to any meaningful effect (Brüggemann et al., 1997; Fedotova, 2010) When the researchers studying the 1994 Olympic field of athletes limited the sample to only the top 15 finishers, the start time in Lillehammer became nearly irrelevant to finish time ($r^2 \approx 0.0$) and showed only trivial relationships to the subsequent splits (Brüggemann et al., 1997). Moreover, it was identified that in Lillehammer specifically, turns 4-10 are where the relationship between split times and finish time rapidly starts to strengthen, which implies that this is a critical section of the track for the athletes to be competent at navigating in order to have success against the world's best (Brüggemann et al., 1997). In luge, it appears that that it is very unlikely to place well without a generally competitive start, but it by no means guarantees success at the highest levels of luge competition.

Skeleton. Of all three sliding sports, skeleton is the most frequently studied, perhaps because of the relative ease of doing so, given the individualization of the sport, or possibly because of sport-culture differences between bobsled teams and skeleton athletes. Fedotova (2010) also examined skeleton start times in relation to split times in Lake Placid from 2005-2009 in the North America Cup, World Cup, Intercontinental Cup, and world championships. When the primary correlational analysis was carried out on the higher level competitors in the World Cup and the world championships there was a small correlation between start time and finish time ($r = .24$, $p < .05$) (Fedotova, 2010). Fedotova (2010) noted, similarly to Bruggemenn and colleagues' (1997) 1994 Olympics' findings, that when a wider array of athlete talent levels were included in the statistical analysis, the correlations between start time, split times, and finish time increased dramatically. This is likely caused by increased sample size and the likelihood that very poor skeleton athletes are very poor all around athletes and thus, are also very poor starters (Fedotova, 2010). The larger correlations create the illusion of a meaningful relationship where the start time in skeleton might not actually be as predictive of performance as the strength of correlation might lead one to believe (Fedotova, 2010).

A study using skeleton athletes with a of a wide range of sliding experience and skill in 2006 found a larger overall correlation between push times and finish times as a conglomeration of all tracks competed on by all circuits (Zanoletti et al., 2006). This may be an example of a group of athletes with too heterogeneous of skill levels being used to increase sample size, and thus creating a statistically stronger, but less meaningful correlation (Bullock et al., 2009; Zanoletti et al., 2006). It is likely that novice athletes sliding the North America Cup possess both poor sliding and steering ability and poor sprinting and skeleton sled-pushing ability, and that more advanced athletes on the World Cup tend to possess more advanced versions of both skills (Fedotova, 2010; Zanoletti et al., 2006). But, this doesn't allow inference about the importance of the start during a skeleton race; only that athletes tend to get better at both starting and driving as they progress from lower level competition to the World Cup.

Bullock and colleagues' 2009 paper, primarily pertaining to the variability of performance in skeleton racing at the World Cup level, also examined the relationship between various split intervals from start to finish (Bullock et al., 2009). Push start time correlations with finish time for the top ranked men on the various tracks ranged from $r = -.14$ to $r = .44$ with a mean of $r = .12$ with the women showing slightly stronger more positive correlations at $r = -.09$ to $r = .57$ and a mean of $r = .29$ (Bullock et al., 2009). In general, as was identified in the other non-bobsled studies thus far, the more technical portions of the track, and split times covering portions of the track nearer to the finish are more strongly associated ($r \approx .7$ to $.8$) with race outcome than start performance (Brüggemann et al., 1997; Bullock et al., 2009; Fedotova, 2010).

Bobsled. All studies to date on bobsled racing, with regard to start time, velocities, split times, and finish time, have failed to specifically analyze the relationship between start time and the subsequent split times on a track by track basis (Brüggemann et al., 1997; Morlock & Zatsiorsky, 1989; Smith et al., 2007). The two studies on the 1988 and 1994 Winter Olympic Games in Calgary and Lillehammer, respectively, only correlate start time to finish time, and split times to finish time. While this is certainly the most direct means of inferring a relationship of the start time to finish time in bobsled racing, it may not be sufficient in identifying a competitively meaningful effect that the start has on the upper portion of the track. The same can be said for all analyses of sled velocities as well. That is, there have been no analyses of how upper portions of the track directly influence the immediately subsequent sections of the track in either the velocity or time domain. All analyses have been carried out examining only the relationship of finish time to variables farther up the track. From a strictly statistical sense this finish-time-focus conforms with the goal of the studies, which is to identify factors that may directly influence the outcome of the race, but may allow overlooking of important relationships start to split relationships on a track-by-track basis. Peter Dabnichki, a prominent analyst of bobsled mechanics, in agreement with physical intuition, makes the point that the start should serve as an opportunity to maximize velocity at the beginning of the track, rather than to move with the lowest time through the start zone (Dabnichki, 2016). Understanding of the nuanced interplay between start time and velocity with the subsequent split times and intermediate velocities might be able to guide more educated decision-making about training goals and benchmarks for elite push athletes.

In a recent study carried out at the beginning of the pre-Olympic-year sliding season with a very simple design with regard to identifying the relationship between start time and finish time found a strong relationship between the two ($r = .63$, $p = .05$) (Smith et al., 2007). However, this study may have been performed using mostly low level bobsled athletes vying for spots among the national and developmental teams in the US, creating a very disparate array of talent, which could have created a misleading correlation (Smith et al., 2007). The study by Smith and colleagues in 2004 was carried out during national team testing and more than half of the push times used in their data were more than three tenths of one second slower than the track record push start (Smith et al., 2007). In international level competition on the Lake Placid track where testing took place, it is unlikely that more than a couple of the top 20 sleds would have such a slow push time (Federation, 2016f). It is likely that in this study, the less talented pilots only earned opportunity to have lower-level push athletes push with them, thus falsely inflating the correlation between start and finish times (Smith et al., 2007). Further, the authors grossly misrepresented data from the study on the 1994 Olympic Games by Bruggeman, Morlock and

Zatsiorski, (1997) when they implied that 77% of the race outcome was predicted by push time (Smith et al., 2007). This is an example of exactly the aforementioned concern expressed by Fedotova (2010), regarding inflated or misleading correlations due to disparate performance levels being included in the analysis. The authors of the study in Lillehammer discussed this clearly with regard to the predictive validity of the push start time, and its rapid reduction in validity, as the pool of teams analyzed was consolidated to the top 15, rather than the top 30 (Brüggemann et al., 1997).

In Morlock and Zatsiorski's (1989) paper on the 1988 Games they reported that the correlations between intermediate start times and finish time taken every five meters within the start zone started out moderate ($r = .5 - .6$, all $p < .05$) and then decreased through the end of the IBSF-measured start phase and through turn 5 ($r \approx .45$, all $p < .05$). Split time correlation coefficient continued to increase upwards of $r = .8$ ($p < .05$) as the sleds approached the finish. Split times were defined in the study by Morlock and Zatsiorski (1989) as the elapsed time from breaking the first timing eye to the breaking of the timing eye recording the present split time. Thus, the crossing of the final timing eye creates a finish time and a split time that is equivalent (Morlock & Zatsiorsky, 1989). It is logical then, that as the sled approaches the finish, correlation between split time and finish time, by this definition, will increase naturally because a continuously larger portion of the data is being accounted for in both related datasets as the sled nears the finish (Morlock & Zatsiorsky, 1989). Separate analysis of the correlation of push start time in individual heats to finish time resulted in correlations ranging from $r = .53$ to $r = .74$ with a combined start time to finish time correlation for all heats of $r = .46$ (Morlock & Zatsiorsky, 1989).

When this combined correlation coefficient was adjusted for ice temperature and sled order effects, the correlation of push time to finish time improved to r = .55 (Morlock & Zatsiorsky, 1989). All correlations listed as statistically significant in the study were noted to be significant ($p < .05$) which may be one of the biggest limitations when making specific inferences about the meaningfulness of the data because nearly 300 correlations were reported between all variables with no correction to reduce instances of type 1 error (Morlock & Zatsiorsky, 1989). The statistical significance, as measured by p-values and standard null hypothesis testing is likely not the most useful way to interpret sport data from elite level competition, but relying on the p-values reported without a Bonferroni correction when there have been so many significance tests performance that it is nearly assured that there is type 1 error present may also be a gross over-assumption of actual statistical significance and probably meaningfulness (Batterham & Hopkins, 2006; Hopkins, Marshall, Batterham, & Hanin, 2009).

Other studies have characterized split times differently and compared finish time to specific intervals within the track, for example the time taken to travel the distance between two intermediate timing eyes (Fedotova, 2010). The approach of teasing out specific intervals of sled travel was also employed by Morlock and Zatsiorski (1989), and in the case of the 1988 Olympics in Calgary, they were able to identify one specific interval, a “turn time” of turn seven, that was predictive of 92% of the variability in finish times (Morlock & Zatsiorsky, 1989). Similarly, at the Lillehammer Olympic Games, Bruggemann and colleagues (1997) were able to identify a specific series of turns through which the relationship between rank order of finish was nearly decided.

Push Start Time Relationship to Push Start Velocity

It is presently understood, intuitively, by most people involved in the sport of bobsled, that start time is very closely related to start velocity. Start velocity is a common criterion in discussion among national team coaches and athletes and it is recognized by a leading biomechanist, who is expert in bobsled, that velocity may be the most important factor in determining the relative success of a team's start phase (Dabnichki, 2016). Decisions surrounding team composition and selection are often made with start velocity comparisons at the forefront of discussion. Thus, an investigation of the interrelationship between start time and start velocity, both in totality, and on a track-by-track analysis is warranted.

Only one study to date has examined this relationship specifically, (Bullock et al., 2008) though others have reported velocity data, but only as an explained variance with regard to finish time, (Brüggemann et al., 1997) or to highlight differences between groups, (Morlock & Zatsiorsky, 1989) rather than investigating any relationship to start time or spatially-nearer splits or velocities. Rather than using track-specific measures of sled velocity and determining their relationship with push time like others have done, (Brüggemann et al., 1997) Bullock and colleagues (2008) standardized the location and method of measurement of velocity by gathering their own velocity measures at 15 and 45 m from the start block. These data, all collected on World Cup female skeleton athletes at Sigulda, St. Moritz, and Lake Placid, were then used in various combinations along with time to load and time to 15m, as predictors of push time (measured as is standard by IBSF) (Bullock et al., 2008).

Given that the study in discussion with regard to two measurements of start velocity and their relationship to start time is so methodically similar to the present author's first study presented in Chapter 3 of this manuscript, the 2008 study by Bullock and colleagues merits in-depth review. For inclusion into the currently examined women's World Cup skeleton push start paper, at least one top 20 finish on one of the three aforementioned tracks was required, resulting in 28 total female skeleton athletes competing on the World Cup being analyzed (Bullock et al., 2008). Temporal analysis was carried out using 50 Hz video footage and a hand-digitizing process resulting in .03 m/s velocity error (Bullock et al., 2008). Technical failure causing no velocity to be captured in Lake Placid resulted in "time to 15m" to be the research team's proxy for an early acceleration value during the Lake Placid race (Bullock et al., 2008).

Stepwise regressions were performed to predict 50-m skeleton push start time using four different start variables including velocities at 15 and 45 m (Bullock et al., 2008). Table 2.6 outlines the various regressions and their corresponding R^2 values (Bullock et al., 2008). Inclusion of velocity at the 15-m line in their regression analysis always returned the most predictive model, and by itself, it was predictive of approximately 85% of all variability in start time (Bullock et al., 2008). Interestingly, while "time to 15 m" did not serve as a good proxy for velocity at 15 m in Sigulda or St. Moritz, where it only predicted ~50% of the variability in velocity at 15 m, it presumably worked much better in Lake Placid as is referenced by the 4th predictive model exhibiting a higher adjusted R^2 value in Lake Placid as compared to St. Moritz and Sigulda (Bullock et al., 2008).

Table 2.6. Adjusted R^2 Values for the Stepwise Multiple Regression Used to Predict Start Time

Model #	Independent Variables			Adjusted R^2 Sigulda	St. Moritz	Lake Placid
1	Velocity at 15m			0.84	0.87	
2	Velocity at 15m	Time to Load		0.87	0.86	
3	Velocity at 15m	Time to Load	Velocity at 45m	0.88	0.9	
4	Time to 15m	Time to Load	Velocity at 45m	0.68	0.78	0.86

Adapted from: Bullock, N., et al., *Characteristics of the start in women's World Cup skeleton.* Sports Biomechanics, 2008. **7**(3): p. 351-360. (Bullock et al., 2008)

The inclusion of two separate velocities measured 30 m apart, in their predictive model for 50-m start time, resulted in the highest adjusted R^2 values (Bullock et al., 2008). This is still intuitive, in that, the more often a velocity reading is taken, the more accurately one will be able to interpolate the time taken to cover the distance, essentially increasing frequency of sampling in a mathematical integration problem. Bullock also highlights the need for the exploration of the relationship between terminal start velocity and the second and third splits during the upper third of the track (Bullock et al., 2008). Practically, it is thereby important for athletes to be able to accelerate rapidly so that high velocities can be attained before entering the 50-m timing zone but the relationship between start time and velocity and the subsequent split times is yet relatively unexplored (Bullock et al., 2008).

Biomechanical Analysis of the Start in Sliding Sports

While the depth of the current literature on the relationship between push start time and velocity and split times or finish times is currently limited, all sources, both scientific and athletic, appear to agree that there is likely some meaningful relationship between the characteristics of the push start, and the results further down the track (Brüggemann et al., 1997; Bullock et al., 2009; Fedotova, 2010; Morlock & Zatsiorsky, 1989). To thoroughly understand the demands of the push start and what physical capacities the bobsled push athlete needs, first, an examination of the physical task at hand is warranted. Remarkably the sport of bobsled had been in existence in international competition for over 100 years before the first study on the mechanics of the push start was published (Federation, 2016d; Smith et al., 2007). Less remarkably, there have yet to be any useful studies published with regard to kinetics because the data is so challenging to collect during the push start of skeleton or bobsled (Dabnichki, 2016).

But, several studies have now examined portions of the kinematics expressed during skeleton and bobsled push starts (Colyer, 2015; Kivi, Smith, Duckham, & Holmgren, 2004; Lopes & Alouche, 2016; Park et al., 2016; Park et al., 2015; Smith et al., 2007).

Unfortunately, the quality of studies examining kinematics in sliding sport starts(Lopes & Alouche, 2016) and their relevance and usefulness for informing decisions(Park et al., 2016; Park et al., 2015) in training or competition strategy has paled in comparison to the depth and quality of kinematic analysis in biomechanically similar motions like sprint running (Coh, Colja, Dolenec, & Stuhec, 1998; Coh, Peharec, & Bacic, 2007; Coh & Tomazin, 2006). One such study only examined the joint angles of brakemen during the “hit” of the sled where the first acceleration of the sled from the starting block takes place, as well as the joint angles present during first contact on the ice of the first foot to leave the starting block (Lopes & Alouche, 2016). Not only did they find no differences in any joint angle between various stratifications of competitors at the world level, some of their data are rather suspect (Lopes & Alouche, 2016). For example, elbow angles are reported almost completely unchanged at ~180 degrees (completely straight) for all athletes from the time they the break the inertia of the sled to the time that they initially contact the ice with their first step (Lopes & Alouche, 2016). Given that the typical technique of all brakemen at this level is to lean aggressively forward and then rapidly extend the joints of the lower extremity, (Lopes & Alouche, 2016) followed by rapid changing of hand position on the rear handles of the sled, the reporting of elbow joints without meaningful movement (flexion) during this phase is highly suspect.

Figure 2.12. Elbow Angle Change Demonstration in an Elite Brakeman During Initial Bobsled Acceleration. From left to right: Initial “hit” and accaleration of sled, first foot movement off block, fist foot contacting ice. All frames show different elbow angles, contrary to reports in Lopes and Alouche article,(A. D. Lopes & Alouche, 2016) and in agreement with Smith, et al.(S. L. Smith et al., 2007) Adapted from: Skeleton, I.B.a. *Whistler | BMW IBSF World Cup 2016/2017 - 2-Man Bobsleigh Heat 1 | IBSF Official*. 2016 April 10, 2017]; Available from: https://www.youtube.com/watch?v=_kQPuZuL1H4. (Skeleton, 2016)

In fact, it is apparent under visual inspection of footage of any bobsled race in the last 2 decades, that the elbow angle does change quite dynamically during this phase of the start, before the first foot contact is made, as is clearly depicted in Figure 2.12 (Skeleton, 2016). The inane simplicity with which Lopes and Alouche report that “the brakeman touch the ground with a flexed leg,” which is also a strategy “adopted by track race athletes,” and the fact that this was the totality of their lone discussion of the joint angles exhibited by brakemen, makes their analysis useless to sport scientists, coaches, and athletes.

The analyses by Park and colleagues were essentially only a forefoot analysis with the intention of providing data for a bobsled shoe design for the Korean National Team (Park et al., 2016; Park et al., 2015). Interestingly, during this Korean team's preliminary study, they identified that the faster pushing athletes may have lower range of motion at the hip and knee during the first 15 m of pushing than slower athletes during the same phase, however, ankle range of motion was larger in the best pushers (Park et al., 2015). This finding is in alignment with a general conception among bobsled athletes and some coaches that "low heel recovery" is desirable during the initial start phase because reduced knee flexion range of motion would effectively keep the foot closer to being in contact with the ice. Further, higher ankle range of motion during sprinting is in opposition to what is normal in top speed running, where knee and hip range of motion is usually relatively large while ankle range of motion is more limited in the best sprinters (Kunz & Kaufmann, 1981). Perhaps in resisted sprinting, such as is the scenario in bobsled push starts, increased ankle range of motion is a desirable trait that may be predictive of athlete performance, since it appears in the mechanics of faster pushers (Park et al., 2015). These results are also in alignment with a recent finding by Hoffman and colleagues that longer ground contact times during sprinting are predictive of sled pushing speed (Hoffman Jr., 2014). Ankle range of motion is an area that merits future research for the purpose of identifying push athlete talent.

Of the three remaining studies on kinematics of sliding sport push starts, two were examinations of skeleton athletes only (Colyer, 2015; Kivi et al., 2004). Kivi and colleagues (2004) studied the top-6-ranked skeleton athletes in the US in 2013 and looked for differences in kinematics and push result between two starting styles. In general, it was concluded that there were subtle, and potentially meaningful differences in contact and flight times between groups, but that the groups had statistically identical push times (Kivi et al., 2004). Unfortunately, the research group did no other measurement of push result than the time measured at 65 m from the block, even though they were analyzing the potential kinematic differences in the first 5 m of the start, and the effects of those differences (Kivi et al., 2004). Without a much shorter intermediate timed zone, or velocity measurement taken far earlier in the start, the data on kinematics serve no purpose outside of general reference as descriptive data for joint angles and contact and flight times found among skeleton athletes (Kivi et al., 2004). The utility of such data is truncated for sport scientists and coaches, and it is proposed that future research on push starts in sliding sports always include, at a minimum, data collection for multiple timed zones around the start area of interest, if not the entire length of the start zone as well as velocity data of the sled or athlete, via accelerometry.

The most comprehensive review of a sliding sport start has come from Steffi Colyer's 2015 doctoral thesis. Colyer (2015) demonstrated that the skeleton athletes tend to adopt a higher average step frequency and shorter time to load when the push track is shorter or steeper as is the case when Winterberg is compared to Altenberg or the specific dry land push track studied. Intuitively, there was a very strong correlation between average start velocities at the dry-land push track used in testing and the Winterberg and Altenberg ice-tracks, although the correlation between start times at the push track and average velocities was stronger in Winterberg (Colyer, 2015). Further research is certainly necessary to identify contributory factors in the start phase of the skeleton race, although Colyer (2015) presents a strong case for velocity-oriented training to predominate, given the high speeds and low absolute forces encountered by the skeleton athletes. The interrelationship between athlete testing and the start performances discussed previously is discussed in detail in the subsequent related section of the present literature review. It is possible that bobsled pushing may exhibit similar kinematic characteristics and therefore impose similar demands on the athletes.

The only useful study, which set out with the purpose of exploring bobsled push start kinematics, used a wide range of brakeman talent levels as is characteristic of competitions determining the US National Team (Smith et al., 2007). Given that the very best competitors in sprinting may perform using different strategies or more advanced technique or application of force, the analysis of sub-elite competitors and the inclusion of their data with the data from elite level competitors may obfuscate the results that are characteristic to the highest level athletes (Kunz & Kaufmann, 1981; Slawinski et al., 2010). Because of this, the analysis completed by Smith and colleagues is potentially less meaningful for informing strategies in the enhancement of the push start in elite level bobsled athletes (Smith et al., 2007). It would be useful to the research community to do such a reporting study on the top three brakemen in the most successful nations in bobsled, or to examine the mechanics of only the top 6-10 pushing teams at a world level championship, however, the cost and feasibility of such a study are major barriers to overcome. The benefit, as Coh and Tomazin (2006) has performed on a single national champion and world championship level sprinter, would be substantial as a means to create an "ideal technical model" for bobsled pushing, towards which athletes and coaches could work.

Biomechanical Foundation of Sprint Running and Acceleration

There is technical similarity between resisted and unresisted sprinting, (Cronin & Hansen, 2006) and there appears to be a repeatable relationship demonstrated between various sprint tests and sliding sport push start performance (Colyer, 2015; Colyer, Stokes, Bilzon, & Salo, 2016; Colyer, Stokes, Bilzon, Cardinale, & Salo, 2017; Osbeck et al., 1996). The mechanics of sprint running and acceleration are, thus, an integral foundation for complete understanding of the bobsled push start.

Flat Ground Maximum Velocity Sprinting

It has been indicated since the 1980's that elite sprinters are superior to their sub-elite and developmental counterparts primarily due to a shorter ground contact phase which allows for increased stride frequency (Kunz & Kaufmann, 1981; Mann & Herman, 1985; Mann, Herman, Johnson, Schultz, & Kotmel, 1982; Mero, Luhtanen, & Komi, 1982; Moravec et al., 1988). This finding has since been verified repeatedly, more recently, by Weyand et al. (2000 & 2010) and Coh et al. (2001) among others (Bezodis, Kerwin, & Salo, 2008; Kanaoka, 2005). Short ground contact times are generally created by optimal foot placement relative to the athletes center of mass (Deshon & Nelson, 1964; Mann, 1985) and their ability for high rates of force development relative to their own mass (Weyand et al., 2010) due to lower limb stiffness at the knee and in the ankle plantarflexor musculotendinous structures (Bezodis et al., 2008). The necessity of optimal foot placement is created by a need to reduce braking ground reaction forces to minimize the need for propulsive forces, and to reduce power dissipation at the ankle (Bezodis et al., 2008). Rapid repositioning of limbs for optimal foot placement, high stiffness and relative strength, and high hip power are all pieced together to create maximum velocity, which will be limited by the minimum amount of time needed for the athlete to produce sufficient force for a the subsequent flight phase (Weyand et al., 2010).

Maximum Velocity Implications in Bobsled

It is likely, while pushing a bobsled, that maximum velocity sprinting or very-near maximum velocity sprinting will be limited by the same factors because of the mechanical similarity from simple visual inspection, although no analysis has been carried out investigating the specifics of stride biomechanics beyond the first few steps of the sled push (Bullock et al., 2008; Colyer, 2015; Smith et al., 2007). However, during a bobsled push, a portion of the athletes' bodies can be supported by the handles through which the athlete is applying force to the bobsled (Dabnichki, 2016). Depending on the magnitude of this supported weight and it's percentage of total weight, this may meaningfully change the relative importance of various limitations to sprint speed because of the athletes' reduced effective body weight, because the factors primarily responsible for limiting maximum sprint velocity are vertically oriented (Bezodis et al., 2008; Weyand et al., 2010; Weyand et al., 2000). Vertical rate of force development is primarily provided by the ankle and knee joint during the first half of stance and is expressed as "negative power" because of its power dissipation effects (Bezodis et al., 2008).

The required magnitude of rate of force development via stiffness and high contractile velocity ability of the ankle plantarflexors may be decreased because of the vertical application of force to the push bars or handles that is possible during the latter phases of a bobsled push. Thus, athletes who have relatively lower maximum running velocity but high hip power, as Bezodis, Kerwin and Salo (2008) discussed, (along with good execution of pushing technique) may still be highly successful as bobsled push athletes if their limited maximum sprint velocity is principally caused by lower tissue stiffness at the ankle joint. Indeed, there are examples in numerous bobsled federations of highly powerful athletes with peculiarly low sprint speed who have been successful brakemen at the world level.(Skeleton, 2017a, 2017b) Likewise, there have been numerous elite sprinters, who presumably have had very high tissue stiffness, who have not excelled in bobsled pushing performance, and this topic exactly has been discussed by another leading biomechanist (Dabnichki, 2016; Skeleton, 2017e) Further, the relative importance of the maximum velocity ability in both skeleton and bobsled push starts may be somewhat decreased as compared to its importance in track and field sprinting events, because in bobsled there is no maximum velocity maintenance phase, (Colyer, 2015; Dabnichki, 2016) as is common to the short sprints in track and field (Kanaoka, 2005; Mann & Herman, 1985). Vertical rate of force development and ground contact time as limiting factors in bobsled pushing performance is a topic in need of further research.

Flat Ground Acceleration

The skill of acceleration in running has been studied for over 80 years with the focus of the early research identifying force vectors from blocks and optimal positions to start from for track and field performance optimization (Dickinson, 1934; Henry, 1952; Kistler, 1934; Tuttle, 1933; White, 1935). Since then, force-time characteristics, (Henry, 1952; Williams, 1953) various starting positions (Menely & Rosemier, 1968; Vagenas & Hoshizaki, 1986) and proposed strategies, (Pierson, 1963) electromyography, (Mero & Komi, 1990) and kinematics (Coh et al., 2007; Coh & Tomazin, 2006; Lopes, 1951) and kinetics of elite athletes have been described in detail. For the purpose of bobsled, reaction time is left out of discussion because teams are not required to react to a command to initiate their starts in sliding sports (Federation, 2016e).

To summarize, sprint acceleration is primarily a function of high relative power output through coordinated movement of limbs to optimize the relationship between horizontal and vertical ground reaction forces for maximum horizontal impulse to be applied during repeated high-speed foot contacts. One of the most in depth kinematic analyses ever carried out was a case study by Coh and Tomazin (2006) examining the first 12 foot contacts after block exit in a sub-elite sprinter. In general, sprint starts are characterized by longer contact phases and shorter flight times than are seen during top speed running (Coh & Tomazin, 2006). As the athlete accelerates, the relationship between contact time and flight time gradually reverses orientation, making flight times longer and contact times shorter (Coh & Tomazin, 2006). Initially, in competent accelerators, very short phases of braking force application are present, while the propulsive phase dominates both the duration and magnitude of each foot contact's horizontal force application (Hunter, Marshall, & McNair, 2005; Mann, 1985; Mero, 1988). As an athlete accelerates, that is, gains velocity, their need for vertical force application (Mero, Komi, & Gregor, 1992; Weyand et al., 2010; Weyand et al., 2000) is increased and their ability to produce almost purely propulsive ground reaction forces in the horizontal direction is quickly attenuated (Bezodis, Trewartha, & Salo, 2008; Hunter et al., 2005; Mero et al., 1992).

In the case study by Coh and Tomazin (2006), the sub-elite sprint athlete rapidly reduced ground contact time after the first two steps in contact with the track surface, down to ~.13 s by step 4 from an initial ~.18 s, and eventually by step 10-12, approximately .10 s ground contact time per step at a velocity of ~10 m/s. These data align well with other studies examining ground contact times expected at maximum velocity in well trained or top class sprinters because, with much acceleration left to do, the sprinter in the present study exhibited .10 s ground contact times, making it likely that had he continued sprinting to maximum velocity, a further reduction in ground contact time would have taken place to the .08-.09 s values indicated by other researchers (Kanaoka, 2005; Kunz & Kaufmann, 1981; Weyand, Sternlight, Bellizzi, & Wright, 2000; Weyand et al., 2010).

<u>Acceleration Implications in Bobsled</u>

Important to bobsled in the discussion of acceleration mechanics is the added resistance to acceleration that bobsled athletes will experience because of the well-established mechanics changes in sled pushing with increasingly greater loads relative to the athletes body weight (Bachero-Mena & González-Badillo, 2014; Hoffman Jr., 2014; Kawamori, Newton, Hori, &

Nosaka, 2014). Dabnichki (2016) noted that in 2-man bobsled specifically, the external load of a minimum weight sled (170 kg) was nearly the addition of each of the athletes' body weight as the mass that they would be individually responsible to accelerate. Simply put, this likely resembles a shift leftward on the force-velocity curve given that more system mass is present, demanding some amount greater forces and smaller velocities.

A brief comparison of ground contact times found in bobsled athletes during push starts compared to sprinters during flat ground sprinting immediately highlights the added length of time bobsled push athletes are in contact with the ground (Smith et al., 2007). This longer ground contact time is probably due to the need for greater force application and the need for sufficient time availability to develop such force during the stance phase of a sled-push sprint step, since it is well demonstrated that velocities decrease as external loads are increased (Haun, 2015; Kraska, Ramsey, Gregory et al., 2009; McBride, Triplett, Davie, & Newton, 1999). For a visual display of the differences between ground contact times common in bobsled athletes and sprinters, see Figure 2.13 (Coh & Tomazin, 2006; Smith et al., 2007). The present author proposes that further research be carried out on elite bobsled athletes ground contact time as a part of a pushing performance prediction model that also includes variables to represent athlete unresisted acceleration ability speed, power, and maximum strength. In predicting bobsled pushing performance it appears that the missing link may be in performance prediction is the technical application of athletes strength, speed, and power, and this is discussed further in "Determinants of Bobsled Pushing Performance" in the present literature review (Osbeck et al., 1996).

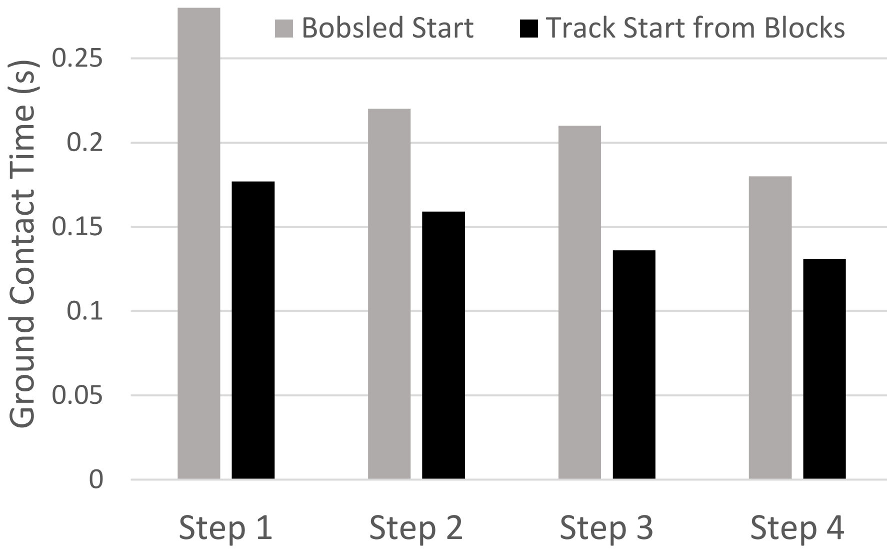

Figure 2.13. Ground Contact Time Differences During Acceleration: Bobsled vs. Unresisted Adapted from: Smith and colleagues,(S. L. Smith et al., 2007) and Coh and Tomazin. (Coh & Tomazin, 2006)

Since the sled weight roughly creates a double-bodyweight sprinting scenario in 2-man bobsled and since athletes can produce greater impulse and force during powerful movements against an external load than they could with no external load, (Kraska, Ramsey, Gregory et al., 2009) and the direct relationship between force production and acceleration, it is reasonable to expect that the sled velocity during the initial acceleration phase before the 15-m timing eye will be somewhere between one half of a sprinters velocity and exactly a sprinters velocity. In 4-man bobsled the external load would be roughly half of body weight per athlete (210 kg empty sled minimum), making it reasonable that in a well-coordinated 4-man push start, the velocity would not be slower than ~67% of that found within 15 m in well-trained sprinters (1 BW ≈ 67% of 1.5 BW). At the fifth total step, or the 4th toe off from ice surface, Smith and colleagues reported average athlete center of mass velocities during a 2-man bobsled push of 5.59 ± 0.40 m/s (Smith et al., 2007). At the equivalent step a sub-elite sprinter is reported to be traveling at 6.98 m/s (Coh & Tomazin, 2006; Smith et al., 2007). Thus, bobsled athletes in 2-man bobsled express roughly 80% of the velocity of sub-elite sprinter examined at step four.

In 4-man bobsled there is no data for velocity directly available, but Morlock and Zatsiorski (1989) reported that in the top 5 finishing 4-man sleds at the 1988 Winter Olympics (which were also most of the fastest pushing sleds) the sleds took an average of .681 seconds to travel the 5 m between a timing eye placed 10 m from the start block to the 15-m timing eye. Because the measurement was taken using the nose of the sled, which results in an effective loss of ~2.5 m acceleration space (Federation, 2016e) to the 10-m timing eye, this results in an average velocity measurement being taken at approximately 7.5 – 12.5 m of sled travel (Morlock & Zatsiorsky, 1989). The midpoint (10 m of acceleration space) of this average velocity measurement may not be precisely equivalent to the actual average velocity through the 5 m zone, but it is probably a close approximation and this distance or larger between timing eyes has been used previously to ascertain estimates of sled velocity in sliding sports (Colyer, 2015). With 10 m of effective acceleration space the reported time from the 1988 Olympics (.681 s), these data convert to an average velocity of 7.35 m/s (Morlock & Zatsiorsky, 1989). The velocity for the sprinter in the study by Coh and Tomazin (2006) was approximately 8.0 m/s at 10 m of acceleration depending on interpretation of the data and step number. Thus bobsled athletes in 4-man bobsled express roughly 92% of the velocity measured in the Coh and Tomazin (2006) sprint athlete case study.

By comparison, women skeleton athletes attained velocities of ~6.7 m/s by the 15-m timing eye during two world cup competitions (Bullock et al., 2008). Given that women's sprint times at the elite level are roughly 10% slower than men, (Committee, 2016) and with the assumption that the difference in short sprint (60-100 m races only) (Ransdell & Wells, 1999) ability between men and women is distributed evenly across the race distance any given velocity for the sub-elite sprinter can be assumed to be reduced by roughly 10% to convert to a similarly competitive female sprinter. A 10% reduction in velocity of the sprinter examined by Coh and Tomazin (2006) at 15 m would result in an approximate velocity of ~8 m/s, again using some interpolation between steps to approximate distance covered. Thus, World Cup level women skeleton athletes are moving approximately 80-85% as fast after 15 m of sprinting with a sled on ice as compared to estimated sub-elite women's sprinters (Bullock et al., 2008). Skeleton pushing involves running with a highly-flexed hip angle and steep torso lean angle, which could play a major role in their ability to attain high velocities (Colyer, 2015; Kivi et al., 2004).

Additional Considerations for Acceleration in Bobsled

Two major factors probably influencing acceleration performance in sliding sport push starts, that have yet to be discussed in all comparisons made between sprinter velocities and sliding sport push starts thus far, are the -2° incline that exists in the "push-off zone" leading up to the 15-m timing eye, (Federation, 2016e) and the athletes' potentially enhanced ability to produce more purely horizontal propulsive forces because of the reliance on vertical support of some of their own body mass (Colyer, 2015; Dabnichki, 2016). Sliding sport athletes experience higher velocities and accelerations than would otherwise be expected on a flat surface with equivalent load because the -2° incline serves to provide some amount of acceleration to both the sled and their own mass during their initial acceleration phase (Paradisis, Cooke, & Bissas, 1998; Paradisis & Cooke, 2001) Paradisis and colleagues (1998 & 2001) have demonstrated 8.4-9.5% increases in running velocity in physical education students sprinting on a downhill slope of -3°. Thus, it is likely that the -2° slope downhill at the bobsled/skeleton start makes a meaningful difference in teams' and athletes' ability to accelerate even before the 15-m timing eye where the race timing officially starts and where most tracks start to increase the degree of negative sloping (Federation, 2016e; Paradisis et al., 1998; Paradisis & Cooke, 2001).

Finally, it may be the case that bobsled athletes are able to produce greater horizontal impulse during the push start than in sprinting, not only because of alterations in the force-velocity relationship (Bachero-Mena & González-Badillo, 2014; Kraska, 2008) but also because a portion of their body mass can be supported by the handles or push bars. No kinematic analysis of 4-man bobsled pushing has been published to date, so there is currently no evidence for or against this occurring in elite athletes already. This contention merits further empirical testing using force transducers and torque measurements within the handles of a scientifically outfitted bobsled. Even if no vertical support of body weight is occurring, it is possible that simply creating sufficient horizontal force during the first few steps of the push, against the large mass of the sled, could allow the athletes to use a more "aggressive" foot-placement strategy than is possible in pure sprint accelerations. Because of the large positive, horizontal force applied to the sled by the athlete at the push bar or handles, the sled may initially provide sufficient reaction forces in return, that athletes could repeatedly place their feet either directly under, or even just behind, their own center of mass. This more posterior foot placement could allow for smaller range of motion at the hip and knee joints (which may be advantageous before the 15 m timing eye) (Park et al., 2015) and more optimal joint angles for force production (Bazyler, 2013; Beckham, 2015; Beckham et al., 2012) in the initial phases of the push start. This would not be possible in flat-ground unresisted sprint acceleration because of the necessity for increased hip and knee flexion and earlier increases in vertical ground reaction forces to sustain the height of athlete's center of mass throughout the acceleration phase (Hunter et al., 2005; Mero et al., 1992).

Given that velocities are only marginally slower than open sprinting (about 10% and 20% difference between 4-man or 2-man bobsled and sprinting, respectively) (Coh & Tomazin, 2006;

Morlock & Zatsiorsky, 1989; Smith et al., 2007) the difference in kinematics made possible by the added mass may be small, but meaningful. However, though the time differences are only 10 and 20%, respectively between sled pushing and unresisted sprinting, they may effectively be more discrepant from the bobsled athletes downhill running ability than the calculated differences might imply. Not only is gravity acting to assist in acceleration of the bobsled, but it is also enhancing the push athlete's maximum acceleration ability because of the downhill slope, thus there may be a greater "reserve" of acceleration ability, which might allow for greater modification of technique to maximize net horizontal impulse. The technical changes possible to enhance athlete push mechanics, given the added resistance of the bobsled during the push start, merit further biomechanical investigation.

Mechanical Studies of Resisted Acceleration

There have been few studies to examine various forms of resisted acceleration training and the acute changes that happen to kinetics and kinematics at varying degrees of resistance (Hoffman Jr., 2014; Lockie, Murphy, & Spinks, 2003). Sled towing, (Clark, Stearne, Walts, & Miller, 2010; West et al., 2013) sled or prowler pushing, incline sprinting(Paradisis et al., 1998; Paradisis & Cooke, 2001), sprinting with a weighted vest, (Clark et al., 2010) or other commercially available contraptions (Upton, 2011) designed to apply resistance to sprinting are commonly used in training studies, but this is an area where the sport science community seems to have jumped the gun to longitudinal studies (Petrakos, Morin, & Egan, 2016; Rumpf, Lockie, Cronin, & Jalilvand, 2016) before there was sufficient data on the actual mechanics of sled pushing available (Hoffman Jr., 2014). As with many studies in sport science, the research is only as good as the subjects, and in this particular field of study, the subjects studied are especially not generalizable to elite resisted-sprinters like bobsled push-athletes (Bolger, Lyons, Harrison, & Kenny, 2015; Clark et al., 2010; Petrakos et al., 2016).

In general, the immediate kinematic changes seen in athletes exposed to progressively more resistance in acceleration are: decreased stride length (Lockie et al., 2003) increased hip flexion, (Lockie et al., 2003) increased trunk lean, (Lockie et al., 2003) decreased stride frequency, (Lockie et al., 2003) and obviously decreased velocity, in direct relation to the load on the sled (Hoffman Jr., 2014). Remarkably, the studies on kinematics are still very limited and studies with regard to kinetics of sled pushing are non-existent. The vast majority of studies on resisted sprinting are in populations who either lack formal strength training experience, talent, or formal speed training experience, and thus, have very low utility for inference (Petrakos et al., 2016) about elite, or even developmental push athletes, all of whom tend to have well above average power output and strength and/or speed (Osbeck, Maiorca, Amico, & Rundell, 1995; Osbeck et al., 1996).

DeWeese, an expert coach in the sliding sports, and McFarlane a common writer on sprint coaching, among many others, have suggested that various forms of resisted sprinting can be used as a means to encourage motor skill acquisition for elite acceleration ability (DeWeese, Sams, & Serrano, 2014; McFarlane, 1993). Specifically, lowered shin angles and appropriate lean angle during the acceleration phase of sprinting can be coached during the off-season phase while concomitantly improving strength and power so that when the athlete moves into the in-season phase, they are prepared for the mechanical demands of high speed acceleration (DeWeese et al., 2014). However, there is very little published data to justify these intuitive claims about opportunity for alteration of acceleration technique. A study on the Korean bobsled team accelerating with a bobsled for 15 m may have implied that shin angles being lowered was beneficial because of their finding of decreased hip and knee flexion range of motion in elite push athletes as compared to sub-elite push athletes (Park et al., 2015). While the coaching of lowered shin angles is generally an accepted practice in bobsled as well as track and field, the kinetic and kinematic demonstration of its occurrence and benefit in resisted sprinting is still needed.

Determinants of Maximum Sprinting Speed and Acceleration Ability

To thoroughly understand the requirements of bobsled-pushing and what physical capacities push athletes are likely to need, first, an examination of the physical characteristics needed for acceleration and sprinting ability is warranted. Numerous studies have examined differences between relatively fast- versus relatively slow-running athletes or investigated physical characteristics that can differentiate between faster and slower athletes (Kanaoka, 2005; Kunz & Kaufmann, 1981). These cross-sectional comparisons, (Comfort et al., 2012; Comfort, Stewart, Bloom, & Clarkson, 2014; McBride et al., 2009) descriptive or correlational, (Baker & Nance, 1999; Bellon, 2016; Chiang, 2014; Fortier, Basset, Mbourou, Favérial, & Teasdale, 2005; Israetel, 2013; Marques & Izquierdo, 2014; McBride et al., 2009; Sleivert & Taingahue, 2004; Wisløff, Castagna, Helgerud, Jones, & Hoff, 2004) or predictive studies, (Cronin & Hansen, 2005; Dal Pupo, Arins, Guglielmo, da Silva, & dos Santos, 2010) can provide an excellent understanding of traits that are either common to elite sprinters, or should be developed in training of the same. While biomechanical examination of both acceleration and maximum velocity sprinting has been relatively thorough (Kunz & Kaufmann, 1981; Weyand et al., 2010; Weyand et al., 2000) this is not the case for identifying physical determinants of these abilities.

Not surprisingly, physical determinants of acceleration have been investigated much more frequently than those of maximum sprinting ability (Bellon, 2016). This may be due to the need for acceleration ability in team sports (Comfort et al., 2014; Duthie, Pyne, & Hooper, 2003; Gray & Jenkins, 2010; Israetel, 2013; Sheppard, Gabbett, & Stanganelli, 2009; Spencer et al., 2004) or the inability to perform training interventions or testing batteries in track and field athletes where it is somewhat typical for track and field coaches to oversee and guard the training process, as opposed to many other team sports where coaches more often seek assistance from strength and conditioning professionals. The vast majority of reports examining sprinting in the track and field athlete have not included any significant intervention or testing battery, outside of sprints that might already be carried out in the course of normal training and competition, (Coh et al., 1998; Čoh et al., 2001; Coh et al., 2007; Coh & Tomazin, 2006; Kunz & Kaufmann, 1981; Mero, 1988; Mero & Komi, 1990; Mero, Kuitunen, Harland, Kyrolainen, & Komi, 2006; Mero, Luhtanen, & Komi, 1983) whereas in acceleration research in team sports, there are often strength, conditioning, and speed training interventions and testing batteries, presumably approved by the sport coaches (Baker & Nance, 1999; Barr, Sheppard, Agar-Newman, & Newton, 2014; Bellon, 2016; Comfort et al., 2014; Harrison & Bourke, 2009; Kilduff et al., 2007; West et al., 2013).

Determinants of Acceleration: Strength

In alignment with the mechanical analyses of sprint starts indicating need for high ground reaction forces, (Mero, 1988; Mero et al., 1992; Mero et al., 1983) strength, defined as an athlete's ability to produce force, has been repeatedly identified as a foundational physical determinant of acceleration ability and a discriminating characteristic in acceleration in a range of populations (Bellon, 2016; Comfort et al., 2012; Comfort et al., 2014; McBride et al., 2009;

Wisløff et al., 2004). Comfort and colleagues have found reliably strong relationships ($r \approx -.60$, $p < .01$) between absolute and relative strength and sprint acceleration times over 5, 10, and 20 m in recreational and well-trained soccer athletes alike (Comfort et al., 2012; Comfort et al., 2014). Similarly, McBride and colleagues (2009) found squatting strength relative to body weight was related to 10 and 40 m sprint times ($r \approx -.60$, $p < .025$) and that when athletes with 1-repetition maximum (1RM) squat values in excess of 2.1 times body weight were compared to athletes whose 1RM was 1.9 times body weight or less, the stronger group was significantly faster over 10 and 40 yards ($p < .05$). Although the actual group means were not reported, it appears through visual inspection of the figure that the time difference between groups was roughly .2 s and .1 s in the 40 and 10 yard sprints, respectively (McBride et al., 2009). Similarly, in a study of the relationship between three-repetition maximum squat strength and sprint speed over various distances up to 40 m in rugby athletes, researchers revealed several statistically significant and practically meaningful relationships (Baker & Nance, 1999).

Relative strength, as measured by three repetition maximum back squat, has also previously been strongly correlated to 40 m sprint time ($r = -.66$, $p < .05$), and though not statistically significantly correlated to 10-m sprint time, it still predicted 16% of the variability in 10-m sprint time ($r = -.39$, $p > .05$) (Baker & Nance, 1999). In these rugby athletes with a large variation in body masses (mean = 93.4, SD = 11.7 kg), absolute strength was not related to sprint speed (Baker & Nance, 1999). In more homogenous groups of athletes, absolute strength appears to be more related to acceleration ability (Comfort et al., 2012; Comfort et al., 2014). Similarly, Barr and colleagues (2014) reported a statistically significant difference in relative strength, as measured by 1RM front squat, between faster and slower performers over 40-m sprints.

The strongest correlation between relative strength as measured using full range of motion squat, and short sprint performance was demonstrated in 2010 by Nimphius and colleagues in softball players (Nimphius, Mcguigan, & Newton, 2010). While correlations between relative strength and sprint times were between $r = -.75$ and $r = -.85$ ($p < .05$) it is possible that these correlations were inflated because of the very strong relationship between relative strength and body weight and the very wide range in athlete body weights (mean = 72.43 ± SD = 10.82 kg), meaning that body weight may have been as important as, or more important than, strength in these athletes (Nimphius et al., 2010).

In studies using potentially more sport specific joint angles in their strength testing, as opposed to full range of motion squatting, higher relationships between strength and acceleration ability have been identified. Israetel and colleagues (2013) identified a small effect size (ES = -0.32) of allometrically scaled isometric mid-thigh pull peak force and 10-m sprint time in NCAA Division 1 athletes. The same group found that peak force scaled to body mass demonstrated a moderate effect size (% difference = -8.62, ES = 0.55) between fast and slow groups in the 20-m sprint (Israetel, 2013). Using half squat maximums, Wisloff and colleagues (2004) demonstrated a very strong relationship ($r = .94$, $p < .001$) to 10-m sprint time, and a strong relationship ($r = .71$, $p < .01$) to 30-m sprint time, in elite soccer players. The strength of these relationships from the study using half squats, though compelling, have never been repeated and may be inflated due to the very wide range of athletes tested (30-m sprint time ranged from 4.40 s to under 3.60 s, mean = 4.00, SD = .20 s) (Wisløff et al., 2004). Recently, Bellon and colleagues (2016) used NCAA Division I athletes to examine the relationship between a litany of kinetic measurements and velocity at steps 3, 6, and 9, during a 20 m sprint. Of the correlates to velocity at steps 3 and

9 to not reach statistical significance, the highest value was that of allometrically scaled peak force during an isometric mid-thigh pull ($r = .269$ and $.416$, respectively, $p > .05$) (Bellon, 2016).

Nonetheless, it is well-established that there is a moderate to strong relationship between relative strength and acceleration performance, (Barr et al., 2014; Bellon, 2016; McBride et al., 2009; Nimphius et al., 2010) and in homogenous groups of athletes, especially those of similar weight, between absolute strength and acceleration performance (Comfort et al., 2012; Comfort et al., 2014). It is problematic that some researchers seem to question the importance or relevance of strength in isoinertial movements based on their findings of non-correlation to sprint performance when the effect could be explained simply by the large variability in athlete mass, rather than unimportance of maximum strength (J. B. Cronin & Hansen, 2005). Similarly, the range in body mass should be noted in studies where relative strength is calculated, and exhibits a high correlation with sprint speed, so that body weight as a covarying factor with relative strength is not misleading to the importance of strength (Barr et al., 2014; Nimphius et al., 2010).

Determinants of Acceleration: Power

Power is defined as either a work rate, or the product of force and velocity. Given that an athlete's ability to produce force appears related to running acceleration in numerous studies, it is logical that a measure more closely related to speed, in simple physical terms, will also be strongly related to acceleration performance. Indeed, measures of power output ranging from various unloaded and loaded jumping tests, to weightlifting movements have all been shown to predict or relate to acceleration ability (Barr et al., 2014; Bellon, 2016; Comfort et al., 2014; J. B. Cronin & Hansen, 2005; Dal Pupo, Arins, Guglielmo, da Silva, et al., 2010; Hudgins et al., 2013; Israetel, 2013; Marques & Izquierdo, 2014; Sleivert & Taingahue, 2004; Wisløff et al., 2004).

Squat jump performance from a static start position is moderately correlated with velocities in early phases of acceleration (Bellon, 2016). Peak force during countermovement jumps has also been correlated with 10-m sprint times ($r = .47$, $p < .01$) (Marques & Izquierdo, 2014). Large effect sizes (ES = -0.70) between higher jumpers (38.8 ± 8.8 cm) and lower jumpers (27.0 ± 4.8 cm) for sprint time over 20 m were reported by Israetel and colleagues (2013) in NCAA Division 1 athletes. Inversely, but demonstrating a similar effect, faster athletes over 20 m (3.11 ± 0.19 s) compared with slower athletes (3.37 ± 0.20 s) tended to jump approximately 21% higher during an unweighted countermovement jump, demonstrating a large effect size (ES = 1.17) (Israetel, 2013). Cronin and Hansen's (2005) findings indicate similarly that countermovement jumps and jump squats with 30 kg are both correlated to sprint performance over five to 30 m ($r = -0.56$ to -0.66, $p < .05$). Even with the potential interference of speed endurance, Dal Pupo and colleagues (2010) found that within a group of 200 and 400-m runners, 200-m sprint performance could be predicted by countermovement jump height ($R^2 = 0.56$, $p < .05$).

Measures of power in the weighted jump squat, using force and velocity data for calculation, have also been correlated ($r \approx -0.65$, $p < .001$) to sprint time over 5 m (Sleivert & Taingahue, 2004). More recently, power during jump squats relative to body weight, using loads ranging between 0-80% of 1RM back squat, were found to correlate strongly ($r = -0.76$ to -0.92, $p < .05$) with 20 and 40-yard sprints in softball players (Nimphius et al., 2010). Cronin and Hansen (2005) also report moderate correlations between power relative to body mass in the squat jump with 30 kg and 5-, 10-, and 30-m sprints.

Using the power clean weight divided by body mass, Barr and colleagues found a very meaningful difference (ES = 1.2, Large) in performance between fast (1.30 ± 0.13 kg/kg) and slow (1.14 ± 0.13 kg/kg) groups in a 40-yard sprint (Barr et al., 2014). Unfortunately, it appears that body mass may have played a significant role in the creation of the large effect size and the present author suggests that, in the future, researchers find ways to identify to what degree a potential difference between fast and slow athletes is created by body mass, rather than by strength and power differences. A similar story is told by Baker and Nance (1999) again in rugby players. Power during jump squats with loads from 40-100 kg, relative to body mass, exhibits moderate to strong correlations to 10- and 40-m sprint performance but absolute strength exhibits no relationship to the sprint times, probably because of the disparate body weights of the rugby players (Baker & Nance, 1999). It might be useful in the future, in order to make more meaningful conclusions about the relationship of strength and power to sprinting performance, to use more homogenous subject pools with regard to body mass so that the covariance of body mass to relative strength and power doesn't become a confounding factor and cause overstatement of the strength/power-speed relationship.

Determinants of Power Performance and Relevance to Bobsled

Given that pushing a bobsled requires athletes to move a heavy external load at high velocities, (Federation, 2016e) it is reasonable to assume that high level power output is necessitated. Like the need for review of various indicators that are related to sprint speed, the investigation of bobsled athletes and their required characteristics should examine the aspects of human performance that may indicate or predict high-level power output when working with an external load, as in bobsled. These indicators, correlates, and predictors may be meaningful indicators for training or monitoring, or may guide decision-making about useful measures by which to evaluate the bobsled athlete. Power performance when working with fixed loads, such as is the case in bobsled, is related to the athlete's mass, (Hoffman Jr., 2014) strength relative to the external load and to their body weight, (Haun, 2015; Israetel, 2013; Kraska, 2008; McBride et al., 1999) and their absolute strength (Haun, 2015; Hoffman Jr., 2014; Kraska, Ramsey, Gregory, et al., 2009; McBride et al., 1999; Santana, 2016; Swisher, 2009).

In general, stronger athletes have repeatedly been shown to exhibit greater jump heights with equivalent loads, and greater power output with equivalent loads as well as load prescribed as a percentage of their maximum strength (Haun, 2015; Kraska, 2008; Kraska, Ramsey, Gregory, et al., 2009; McBride et al., 1999). Two groups of researchers have now demonstrated that stronger athletes experience less drop-off in jump height and peak power during jumping exercises, when increased loads are applied (Haun, 2015; Kraska, Ramsey, Gregory, et al., 2009). This relationship is especially pronounced as the absolute loads become larger (Haun, 2015). Specifically, the percent change in jump height in males moving from an unweighted jump through five total jump weights, up to 185 pounds was increasingly correlated ($r = 0.42$, 0.56, 0.65, and 0.7, $p < .05$) to absolute strength as the load became heavier (Haun, 2015). This may be especially applicable to bobsled athletes since the sled weight is relatively large in comparison to body mass, and since any decrease in athlete body mass from effective maximum allowable crew weight is usually added to the sled to ensure a near-maximum-weight sled is being used in competition. Potentially even more applicable since athletes are generally large in bobsled (90-110kg), Haun and colleagues (2015 & 2017) reported that the ratio between jump height (cm) and system mass of loaded vertical jumps from zero to 185 pounds (ratio reported in cm/kg) was increasingly correlated with absolute and relative strength over the five loads used in jumping ($r = 0.28$, 0.41, 0.47, 0.50, 0.53 and $r = -0.07$, 0.09, 0.27, 0.37, 0.47, respectively).(C. Haun et al., 2017; C. T. Haun, 2015) Essentially, as system mass gets larger, the ratio of jump height to system mass is affected to larger and larger degree by absolute strength (Haun et al., 2017; Haun, 2015).

Similarly, Kraska and colleagues (2009) identified that the drop off when comparing loaded (20 kg) to unweighted, vertical, countermovement and static start squat jumps, was smaller in the stronger group (17.4 ± 4.8% and 17.8 ± 3.4%, respectively), as compared to the weaker group (34.5 ± 7.8 % and 30.4 ± 7.8%, respectively). Moreover, athletes jumping ability in static-start squat jump of 0 and 20 kg and countermovement jump of 0 and 20 kg were all moderately correlated ($r = 0.48, 0.66, 0.43, 0.62$, $p < .05$) to absolute strength as tested by a an isometric mid-thigh pull. Importantly, the more heavily-loaded jumps were more strongly correlated with a sport-specific strength position like the mid-thigh pull (Haun, 2015).

This is in alignment with the findings of Haun and colleagues and appears to support the notion that strength cannot be overlooked when athletes are required to move powerfully against external loads (Haun et al., 2017; Haun, 2015; Kraska, Ramsey, Gregory, et al., 2009). In further corroboration of strength in sport-specific joint angles being related to jumping ability, Santana and colleagues found positive correlations between two methods of jumping performance and various methods of normalized force calculations as well as non-normalized force during isometric mid-thigh pull tests with two slight variants in setup (Santana, 2016). These authors reported that absolute strength values were generally more strongly related to jumping performance than the normalized force values were, further highlighting the importance of strength in power performance (Santana, 2016).

Numerous other studies have also reported on the relationship of maximum strength to power production through a litany of tested power-related variables during jumping exercises

(Carlock et al., 2004; Stone et al., 2004; Stone, O'bryant, et al., 2003; Stone, Sanborn, et al., 2003).

Carlock (2004) reported near-perfect correlations (r = 0.92, 0.93, p < .05) between 1RM back squat and peak power during a countermovement jump and static-start vertical jump in weightlifters. Countermovement jump and static-start vertical jump height were also moderately correlated (r = 0.52, 0.58, p < .05) to 1RM back squat (Carlock et al., 2004). When 1RM back squat was scaled to body weight the correlations to the same jumping heights became stronger (r = 0.76, 0.69, p < .05) (Carlock et al., 2004). In the same study there were also a near-perfect correlations between 1RM back squat and 1RM snatch and clean and jerk (r = 0.94, 0.95, p < .05) (Carlock et al., 2004).

Stone and colleagues have also demonstrated that isometric peak force is strongly related to peak power and weightlifting performance (Stone et al., 2004; Stone, Sanborn, et al., 2003) Further, Stone's (2003) research group has demonstrated across a spectrum of loads as a percentage of 1RM back squat that during two types of jumps, peak power capabilities of stronger athletes are superior to those of weaker athletes, with moderate to large effect sizes. In short, it is quite well-demonstrated that stronger athletes are more powerful in nearly every reliable measure of power, from jumping and cycling, to throwing and weightlifting movements and their derivatives (Carlock et al., 2004; Haun, 2015; Hoffman Jr., 2014; Israetel, 2013; McBride et al., 1999; Santana, 2016; Stone et al., 2004; Stone, O'bryant, et al., 2003; Stone, Sanborn et al., 2003; Swisher, 2009).

When external load is fixed, or even reduced as a result of increasing athlete size, as is the case in the sport of bobsled because of the IBSF rules on maximum sled weight, (Federation, 2016e) it is reasonable to conclude that increasing athlete size and maximum strength may become especially advantageous alongside speed and power training (Haun, 2015; Hoffman Jr., 2014; Kraska, 2008; Kraska, Ramsey, Gregory, et al., 2009). In the most specific investigation of the relationship between maximum strength to power in resisted sprinting to date, Hoffman and colleagues found exactly that (Hoffman Jr., 2014). Researchers reported that heavier athletes generally pushed sleds faster even though sled weights were percentages (75, 100, and 125%) based on body weight (Hoffman Jr., 2014). While statistical significance was not reached, in terms of standard hypothesis testing regarding differences between strongest athletes and weakest athletes and their sled-pushing performance, in the two heavier sled scenarios, there were meaningful differences between groups in peak velocity as well as the percent difference between peak loaded velocity and peak velocity during sprinting (Hoffman Jr., 2014). This finding of decreased performance decrements in stronger athletes as external loads increase agrees with all other literature, but appears to be the first demonstration of this relationship in a resisted sprinting scenario (Hoffman Jr., 2014).

Determinants of Bobsled-Pushing Performance

One of the most valuable contributions science has made to sport is to assist in the elucidation of relationships between various athlete characteristics and sport performance. The value in such studies lies in talent identification, informing decisions regarding athlete training and monitoring, and predicting performance capability. As such, reviewing the available literature relating various physical tests and athlete measurements to sliding sports push starts, and specifically bobsled push starts, may provide the foundation for enhanced recruitment to the sport and performance of the athletes within the sport through better training programming, coaching, and monitoring.

Bobsled Athlete Characteristics

There have been only a small handful of studies examining the characteristics of bobsled athletes, but most are just generic comparison for the sake of comparison to other sports (Kirkendall & Street, 1986; Koutedakis et al., 1998; Stanula et al., 2013). Even fewer have attempted to identify variables that might be meaningful in terms of performance-prediction (Osbeck et al., 1996). Far more numerous are the studies examining skeleton athlete characteristics and abilities (Colyer, 2015; Colyer et al., 2016; Colyer, Stokes, Bilzon, Cardinale, et al., 2017; Colyer, Stokes, Bilzon, & Salo, 2017; Roche, Turnock, & Wright, 2008; Sands et al., 2005). Additionally, two abstracts on the topic in bobsledders were published over 20 years ago. The first examined reliability of an old testing battery and reported very high predictive ability (side-push = 93%, brake-push = 76%, driver-push = 99%) of various sprint times to push track times, but this test was carried out more than 20 years ago and the athlete characteristics have changed immensely since then, as have the push start times (Maiorca et al., 1995; Skeleton, 2017e, 2017f). The second abstract simply reported average body mass (93.1 ± 10.2 kg), body composition (9.9% ± 3.7%) and Wingate test results, but only discussed the interrelation of the aforementioned variables to each other, which is of little utility in determining value to bobsled push start performance (Osbeck et al., 1995). Not surprisingly, fatter bobsledders expressed higher fatigue on the Wingate test, and this is in alignment with other reports that athletes with more fat and less muscle tend to perform poorly compared to their counterparts of the same weight but better body composition (Israetel, 2013; Osbeck et al., 1995).

Through the only three survey-type studies of multiple sports which include bobsledders it becomes apparent that bobsled athletes are usually large, mesomorphic, power-athlete types (Kirkendall & Street, 1986; Koutedakis et al., 1998; Stanula et al., 2013). In one, Olympic bobsled athletes were convinced to be tested on an isokinetic leg extension and leg flexion machine, to compare their peak torque values at various speeds to 14 Olympic oarsmen, 20 professional dancers, and 10 non-athletes (Koutedakis et al., 1998). Unremarkably, although the relevance of isokinetic testing to sport is low, bobsled athletes and oarsmen were stronger than dancers and non-athletes (Koutedakis et al., 1998). When normalized for weight, the differences between all groups became statistically non-significant (Koutedakis et al., 1998). Stanula and colleagues (2013) essentially grouped Olympic sports into various metabolic categories and found that, indeed, the anaerobic-alactic athletes like bobsledders tended to be larger in height, weight, and BMI than mixed aerobic-anaerobic, and predominantly aerobic athletes. Kirkendall et al. (1986) examined differences between “amateur bobsled athletes” mechanical jumping power during a 60-s Bosco test and that of professionals in ballet, college wrestlers, professional American football players, professional indoor and college soccer players, and college basketball players. Bobsled athletes exhibited the highest normalized work though no differences were found between the top five sporting groups: college basketball, amateur bobsled, professional indoor soccer, college soccer, and professional American football (Kirkendall & Street, 1986). The utility of such findings to the sport of bobsled is limited.

<u>Skeleton Athlete Investigation as Means to Identify Bobsled Push Determinants</u>

Speed of running has been the number one predictor of skeleton athlete performance (Colyer, 2015). This is a relatively intuitive predictor since the sled weight in skeleton is usually less than half of the participants body weight, especially in the men’s field (Federation, 2015b). Sands and colleagues also demonstrated the strong relationship between sprint times and push times in skeleton with relationships ranging from $r = .6$ to $r = .88$ ($p < .05$) for various distances of sprints and pushes compared (Sands et al., 2005). Unfortunately, such a wide array of talent levels was included, the findings are of little utility in discriminating good from great sled-pushers. This particular study's range of 30-m sprint times was over half of one second for the men and nearly one full second for the women, indicating that national level skeleton athletes were being compared in the same group as low-level developmental athletes (Sands et al., 2005). In general, it is well-demonstrated that sprint speed is related to pushing speed in skeleton, though it needs further examination in more homogenous groups of athletes in order to enhance the utility of sprint speed in predicting push time (Colyer, 2015; Sands et al., 2005).

Loaded and unloaded countermovement and static start countermovement jumps, and the change in relationship to sprint and sled-push times as weight was increased, also provided insight into the needs for power output relative to body weight in the skeleton athletes (Sands et al., 2005). As weight was increased during jump testing from 0 to 60% of body mass, maximum force (N), jump height (m), and power (W) all became increasingly related to both sprint time and skeleton sled-push time (Sands et al., 2005). Given that skeleton sleds are lighter relative to bobsled, and that multiple groups of researchers have demonstrated the increasing relationship between strength and sequentially larger loads in jumping, this finding may indicate the need for well-standardized strength testing in bobsled athletes as a predictor of sled pushing performance (Haun et al., 2017; Haun, 2015; Kraska, 2008; Kraska, Ramsey, Gregory, et al., 2009).

Determinants Specific to Bobsled Pushing Performance

Osbeck and colleagues (1996) provided one especially valuable study with regard to determining the validity and predictive ability of various physical tests to bobsled pushing performance. The major flaw with the study, however, is the very wide range of athletic ability within the subject pool (Osbeck et al., 1996). The applicability of the study to today's bobsled recruitment environment is limited because half of the subjects are less athletic as measured by the tests, than the poorest quality athletes that are currently invited to the USABS Preliminary Push Championships, annually (Osbeck et al., 1996). For example, in 2014, after the Olympics there were only two US National Team brakemen returning and it was the most novice crew of athletes at USA National Push Championships in at least a decade, and the slowest 30-m sprint time among those athletes was 3.95 s. This, was accomplished using the new methodology of not allowing any rocking at the start to create momentum before breaking the first timing eye (Skeleton, 2017f). The study by Osbeck (1996) included athletes as slow as 4.07 s in the 30-m sprint, likely using the rock-in technique which is probably approximately one tenth of once second faster than the static start (Skeleton, 2017f). In 2015-16, there was no athlete competing at the National Push Championhips with a 30-m time worse than 3.85 s from a static start. So, while Osbeck (1996) reports a correlation of r = .85 and r = .88 for 30-m run time to side- and brake-push times, it is likely that the relationship is enhanced simply by including such poor athletes in the data. Not only has the spread of talent been smaller in the last decade, but the absolute level of performance is better now as well (Osbeck et al., 1996; Skeleton, 2017f).

The underhand shot toss in the study by Osbeck (1996) also likely experienced an inflated predictive validity by the inclusion of three athletes throwing under 12 m, and also predictably performing quite poorly in brake- and side-pushes (r = -0.59 and -0.67, respectively) (Osbeck et al., 1996). Similarly, in side-pushing, although the 15th highest jumping athlete has the fastest side push time, the correlation is still moderate, simply because three athletes with especially poor vertical jump performance (~65 cm using a Vertec) also demonstrated especially poor sled-push performance (Osbeck et al., 1996). The same story is told using vertical jump height as a correlate of brake push time, with the 17th highest jumper out of 26 total athletes, pushing in the top three, and the correlation between jump height and brake push still being enhanced by those athletes with vertical jumps barely in excess of two feet on a Vertec (Osbeck et al., 1996).

The spread in combine variables as discussed thus far isn't the only indicator that a wider array of talent was being studied than what is commonly seen today (Osbeck et al., 1996). The range of push times from the brake- and the side-push is .47 s, on average, whereas in 2015 the range with the same number of athletes is roughly .32 s, a reduction in spread of more than 30% (Osbeck et al., 1996; Skeleton, 2017e). This relative homogeneity of the athletes in the 2014-2016 seasons as compared to the athletes used in the study on US bobsledders at the 1995 National Push Championships will undoubtedly reduce the reported strength of correlation between many of the variables and push performance (Osbeck et al., 1996; Skeleton, 2017e, 2017f).

As might be expected, due to very low amount of time spent running at top speed in bobsled, and the complete lack of speed endurance needed, the longer runs of 60 m and 100 m decreased progressively in correlation strength to push performance, as the runs got longer (Osbeck et al., 1996). Combine events that are so heavily related to body weight as a covariate with their performance, like repeated hopping for distance and vertical jumping, (Barr et al., 2014) are likely to not correlate well with sled pushing ability, given reasonable homogeneity of the group, because greater lean body mass could be expected to assist in sled pushing performance whereas jumping height performance tends to be negatively affected by added mass (Hoffman Jr., 2014; Israetel, 2013; McBride et al., 1999). The USABS has since done away with vertical jumping, multiple jump performance, 60- and 100-m run time as scored items on the 6-item combine (Skeleton, 2017f). It has since replaced these items with a single broad jump, a 15-m and 45-m run as well as a 30-m "fly"(Skeleton, 2017f). Additionally, once an athlete hits a threshold score (much higher as a percentage of maximum score, now, compared with 1995) (Osbeck et al., 1996) the athlete is invited to Lake Placid to complete the 8-item combine and participate in USA Preliminary Push Championships where all rookies compete for the first time (Skeleton, 2017f). The additional two items are the 1RM power clean and a 3RM back squat (Skeleton, 2017f). Both of these have closely related to power and strength performances in previous studies (Barr et al., 2014; Stone, O'bryant, et al., 2003; Stone, Sanborn, et al., 2003).

The qualitative focus of the US team has always been increased speed of running, above all (Sato & Suzuki, 1991). Interestingly, Sato and Suzuki (1991) investigated the US, Canadian, Swiss, and Japanese bobsled teams for both their pushing ability as well as each sled's relationship between push time and finish time. The authors quickly admit that Japan is less competitive than the other three nations examined (Sato & Suzuki, 1991). They also identify that American athletes, *including the developmental team,* were approximately .12 s faster, on average, over a 60-m sprint than the Swiss national brakemen and the Canadian national brakemen, and yet the Americans got out-pushed on average by both of those teams (Sato & Suzuki, 1991). The authors highlighted the fact that the US bobsled team may focus too excessively on speed and potentially not enough on the other characteristics that beget competitive push performances (Sato & Suzuki, 1991). These claims of the potential for over-emphasis on speed has recently been reiterated by Dabnichki (2016). According to separate studies by Cronin, McBride, Stone, and Kraska, and their respective colleagues, power performance may be more important, rather than velocity which appears not often to relate well to sport performance (Cronin & Hansen, 2005; Kraska, Ramsey, Gregory, et al., 2009; McBride et al., 1999; Stone, Sanborn, et al., 2003). The speed of the US National Team continues to be a primary focus.

Training Studies in Sled Pushing

One other potential means for interpreting which athlete qualities might provide meaningful insight into their sled-pushing ability is to examine how pushing or other closely related variables (like sprint speed) change coincidentally when such athlete qualities are modified through chronic training. It has been shown repeatedly in untrained, recreational, and well-trained team sport athletes, that sprint speed can be enhanced using resisted sprinting, be it towing, or sled pushing, with external loads that change velocity to no greater than 30% of unresisted sprint speed, or that are no greater than 30% of body mass (Petrakos et al., 2016). It has also been suggested that, acutely, these methods of training could be detrimental for the purpose of sprint speed enhancement because of kinematic changes like increased trunk lean angle and longer ground contact times (Petrakos et al., 2016). However, these kinematic changes might be advantageous for bobsled pushing ability (Hoffman Jr., 2014). Thus, the combination of reliably increased performance in sprinting in moderately training subjects that often coincides with increased power or strength, as well as increased ground contact times in response to resisted sprinting, might be advantageous to bobsled-pushing performance.

Unfortunately, no training studies to date have looked at the effects of sprint training alone, on sled pushing. All current published studies using sled pushing or sled towing are using the resisted sprint modality as a means to increase unresisted sprint speed because of its universality in sports (Petrakos et al., 2016; Rumpf et al., 2016).

Numerous studies have examined the effects of various training modalities on increasing sprint speed, and acceleration ability (Rumpf et al., 2016). In a review of all training methods for the purpose of increasing sprint speed, Rumpf and colleagues (2016) examined unresisted sprinting, resisted sprinting, assisted sprinting, plyometric training, power training, resistance training, and combined training and outlined "efficacy" on a per session basis. Quality of subjects varied from extremely low to reasonably well-trained athletes across all included studies (Rumpf et al., 2016). Of the 48 studies reviewed, the longest study duration was 15 weeks with an average of closer to 8 weeks (Rumpf et al., 2016). Naturally, with such short study durations the most effective means of increasing sprint speed were those most mechanically like acceleration (Rumpf et al., 2016). In general, it was presented that the efficacy of resisted and unresisted sprint training were relatively equivalent means of improving acceleration performance, with potentially a slight advantage being given to resisted sprinting for performance benefits in the shortest measured acceleration bouts (0-10 m, 0-20 m) (Rumpf et al., 2016). Trained athletes in the sliding sports train year-round to improve their push start ability, (DeWeese et al., 2014) and an 8-week study average in mediocre or poorly trained subjects may not be indicative of the most effective means of start performance enhancement in highly-trained athletes (Rumpf et al., 2016). It is possible, given longer term training, that a phasic approach to training, moving from less specific to more specific programming as the need for performance becomes imminent, would provide greater long term athlete development in acceleration and sled-pushing performance. This contention, still in need of empirical analysis, is based on the understanding that strength is highly modifiable over the career of the athlete, whereas continuously increasing speed of acceleration without periodically training for improvements in strength (ability to produce force) will eventually result in diminishing returns in speed training.

Other Potential Determinants of Bobsled-Pushing Performance

In the sled-pushing study by Hoffman and colleagues, the authors reported a somewhat dichotomous finding regarding sprint speed and ground contact time which are normally related, (Kunz & Kaufmann, 1981; Weyand et al., 2000; Weyand et al., 2010) and it may be very informative for talent identification in bobsled (Hoffman Jr., 2014). As expected, Hoffman and colleagues (2014) found direct relationship between strength and sled-pushing ability. But, they reported that speed during unweighted sprinting was correlated ($r \approx 0.65$, $p < .05$) with all measures of sled pushing with 75% of body weight and that ground contact time was inversely related ($r = -0.62$, $p = .04$) with percent decreases in performance between the two heavier conditions. More simply put, faster athletes push sleds faster, but athletes with longer ground contact times push heavier sleds faster. Since all correlations reported were $r = .61$ or larger, it is likely that the researchers experienced limited statistical power due to the limited number of subjects (11 male rugby athletes) (Hoffman Jr., 2014). It is possible that with greater statistical power there may have been more statistical significance attained, and thus, a greater elaboration on the potential dichotomy between needing faster sprinters with longer ground contact times to push sleds effectively (Hoffman Jr., 2014). From a physical standpoint, this is a logical but novel finding, because the goal in pushing an object to maximum speed is to accumulate net horizontal impulse as fast as possible which can only be done with high power and force, and longer ground contact times so that times of force application to the sled are enhanced (Hoffman Jr., 2014). This is a much needed area of research that should rank high among sport scientists in sliding sports because ground contact time may be possible to modify through training and technical models of sled-pushing. And, the magnitude of impact on performance without further enhancement of athlete biomotor abilities is quite large, given the common discrepancies between athlete ground contact times (Smith et al., 2007).

Notably, ground contact times were measured by Hoffman during unresisted sprinting, and it was those values that correlated with sled-pushing ability using loads equivalent to body weight and slightly more weight (Hoffman Jr., 2014). Further investigation may be merited into whether athletes who have naturally longer ground contact times relative to athletes of similar speed, also have some physical characteristics that could be more easily measured other than ground contact time for the purpose of talent identification and athlete recruitment. Given that ground contact time is so highly reliant on lower extremity stiffness (Kuitunen, Komi, & Kyröläinen, 2002) and foot placement, (Kanaoka, 2005) it is logical that athletes with longer ground contact times relative to their equally-fast counterparts have a surplus of hip and knee strength and power, but limited ankle joint stiffness since stiffness doesn't appear to be under control by neurological factors and is more reliant on Achilles tendon properties (Kuitunen et al., 2002).

Strength, an athlete's ability to produce force, is currently an under-studied predictor of bobsled pushing performance, and no studies have directly reported on it. Though, through inductive reasoning, and the findings of Sands and colleagues in skeleton athletes, alongside the findings of researchers examining relationships of power expression as it relates to strength, one might conclude that strength may be a strong predictor of sled-pushing performance (Haun et al., 2017; Haun, 2015; Kraska, 2008; Kraska, Ramsey, Gregory, et al., 2009; Sands et al., 2005). Kraska and colleagues (2008 & 2009) repeatedly report that stronger athletes jump higher when loads placed upon them are lower in relation to their absolute strength. Haun and colleagues (2015 & 2017) reported that athletes jump height became more strongly related to their relative strength as jumping loads increased. These findings taken in combination with the increasing relationships between heavier jumping loads and push start performance in Sands and colleagues study of US skeleton athletes may indicate that strength is the underlying mechanism for success in sled pushing (Sands et al., 2005). Further, given that bobsleds are usually a greater percentage of an athletes body weight than a skeleton sled, (Federation, 2015b, 2016e) it seems likely that bobsled pushing ability would be more strongly related to absolute and relative strength than skeleton sled pushing.

Given that strength is closely tied to lean body mass, it may also be beneficial for athletes to have a relatively large amount of lean mass (Israetel, 2013). Further, since bobsled weight is inversely related to total crew weight, in most cases, and velocity tends to decrease as external loads are larger, (Cronin, Hansen, Kawamori, & Mcnair, 2008; Haun et al., 2017; Hoffman Jr., 2014; Kraska, Ramsey, Gregory, et al., 2009) it is reasonable to assume that increased crew mass could be advantageous. Thus, increased mass of the individual athlete might be predictive of bobsled-pushing performance. Cronin and colleagues also reported that sprint times are faster during weighted vest sprints with equivalent loads to sled pushing (Cronin et al., 2008). This could lend credence to the intuitive notion common in the sport among push athletes that it is "better to carry the weight than to push it." If this notion, and the literature both indicate need for more massive athletes, it adds fodder to the theoretical predictive utility of body mass in sled-pushing performance.

All taken together, sprint speed, power output, strength, body mass, and pushing technique and perhaps some measures of sprint kinematics, may provide the most predictive ability for sled-pushing performance. It is the job of the researcher to distill these characteristics to reliable and valid measures that are easily carried out by sport coaches and strength and conditioning professionals so that the data can be used as both a monitoring tool for national and developmental squad athletes, as well as a talent identification tool to be used at regional recruitment combines.

CHAPTER 3

THE BOBSLED PUSH START: START TIME AND VELOCITY RELATIONSHIP TO EACH OTHER AND TO SPLIT AND FINISH TIMES VARIES IN A TRACK- AND CONDITION-SPECIFIC MANNER

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THE BOBSLED PUSH START: START TIME AND VELOCITY RELATIONSHIP TO EACH OTHER AND TO SPLIT AND FINISH TIMES VARIES IN A TRACK- AND CONDITION-SPECIFIC MANNER

Abstract

Purpose: The purpose of the present study was to elucidate the interrelationship between start time, start velocity, split times and finish time in World Cup bobsled racing. **Methods:** The 2014-15 and 2015-16 World Cup bobsled races' data were included for 11 bobsled tracks. Start time and velocity reliability were investigated using intraclass correlation coefficients (ICC) and paired sample t-tests. The top 20 sleds start time and velocity data were used to predict finish time in independent linear regressions. Start time was also used via independent linear regressions to predict start velocity. Correlations between start time or start velocity were also calculated for all split times in all races. **Results:** Reliability of start time is high (ICC = .94, average) with decreased reliability occurring when snowfall is present. Reliability of start velocity is lower (ICC = .80, average). Start time is highly related to start velocity ($R^2 > .80$, $p < .001$) when confounding variables like unreliable velocity measurement and snowfall are not present, but can diminish to no relationship when confounding variables present. Start time and start velocity predict an average of 39% and 43% of finish time, respectively, ($p < .05$) with wide variance in prediction between tracks. The relationship between both start time and velocity and finish time wanes in the first 400 m of every track. **Conclusions:** The bobsled push start is a meaningful determinant of bobsled racing performance but it's relationship to finish time may be inflated because if high caliber brakemen and materials being paired with high caliber pilots. The relationship between start time or start velocity and finish time exists primarily in the top quarter of the bobsled track, and is present in a track and race condition-specific manner. The velocity-finish time relationship and its utility in judging push performance could be enhanced by increasing reliability and international standardization of velocity measurement.

Key Words: *winter sports, Olympics, sliding sports*

INTRODUCTION

The Winter Olympics are a costly sporting event that is popular the throughout the northern hemisphere and growing in the southern hemisphere. Nearly 100 events are currently contested with almost as many nations competing (Committee, 2016). Some of the most well-known and most popular events are bobsledding races, which have progressed from low-technology to cutting edge, and from wildly dangerous to slightly less so, over the last 100 years. Four man bobsled has been a contested event in the Winter Olympics since 1924 and both 2- and 4-man disciplines have been Olympic events since 1932 (Federation, 2016b).

It is widely accepted by fans and those within the sport alike that the start phase of a bobsled race is a critical determinant of success in the race overall. Two primary studies have elucidated the relationship between the push start and the finish time in sliding sports, and specifically in 2- and 4-man bobsled (Brüggemann et al., 1997; Morlock & Zatsiorsky, 1989). An often quoted saying within the sport is that one tenth of a second difference at the start may become three tenths of one second by the bottom of the track. Statistically, the relationship between start time and finish time is usually in the range of $r = .4$ to $r = .8$, with the magnitude of relationship being largely track-dependent (Brüggemann et al., 1997; Harrison, DeWeese, Sato, Ramsey, & Stone, 2017; Morlock & Zatsiorsky, 1989).

Only Calgary and Lillehammer have been assessed in a similar manner and each only once, more than 20 years ago. Additionally, the analysis of the bobsled track in Calgary examined only the relationship of splits along the track to finish time, in an effort to determine a critical portion of the track (Morlock & Zatsiorsky, 1989). The analysis of the Lillehammer Olympics was similar in nature (Brüggemann et al., 1997). The utility of their analysis for interpreting practice- and race-push start results is limited however because the relationship of the start to subsequent splits or velocities was not investigated.

The only other similar investigations have been in luge and skeleton and have little meaningful carryover into the sport of bobsled because of the vastly different masses and energetic losses experienced between the sports (Brüggemann et al., 1997; Larman et al., 2008).

Shedding light on the relationship and reliability of start times and velocities, split times, and finish times, can help national team coaches and bobsled pilots better interpret cause and effect between push results and variability in split and finish times. If it is understood that split times are only related to the start at a certain distance down the track then coaches, pilots and bobsled mechanics can direct their resources at other rationales for the variability that they see in the time sheets that they are provided during bobsled training and racing heats.

The first purpose of the present investigation is to clarify the reliability of the start variables in World Cup bobsled racing. Second, the strength of the relationship between start velocity and start time is examined. Third, the strength and continuously diminishing nature of the relationship between the two start variables and down-track split times is investigated via correlation analyses. Finally, the percentage of finish time variability that can be predicted on a track-specific basis by the start variables is reported and discussed.

METHODS

Experimental Approach to the Problem

All available data from all BMW IBSF World Cup Bobsled races in the 2014-15 and 2015-16 seasons are used for analyses. Data collected included start times, start velocities, split times, and finish times for each bobsled track. The tracks included in the analyses are presented in Table 3.1.

Table 3.1. Proportional Differences Between Time and Distance Portions of the Start Comprises in Bobsled Racing.

Bobsled Track Location	Competition Length (m)	Percentage of Competition Length Provided by 50 m Start	Portion of Elapsed Time Comprised of 50 m Start		
			% (Mean +/- SD)	Minimum %	Maximum %
Altenberg, GER	1413	3.5%	9.4% +/- .1%	9.1%	9.7%
Calgary, CAN	1494	3.3%	9.4% +/- .1%	9.2%	9.7%
Igls, AUT	1207	4.1%	9.9% +/- .1%	9.7%	10.1%
Konigssee, GER	1251	4.0%	9.8% +/- .1%	9.6%	10.1%
La Plagne, FRA	1508	3.3%	10.1% +/- .2%	9.7%	10.4%
Lake Placid, USA	1455	3.4%	9.2% +/- .2%	9.1%	9.5%
Park City, USA	1335	3.7%	Not Contested in 2014-15 World Cup		
Pyeongchang, KOR	1376	3.6%	Not Yet Contested		
Sochi, RUS	1500	3.3%	8.7% +/- .1%	8.4%	9.0%
St. Moritz, SUI	1722	2.9%	7.7% +/- .1%	7.5%	8.0%
Whistler, CAN	1450	3.4%	Not Contested in 2014-15 World Cup		
Winterberg, GER	1330	3.8%	Not Contested in 2014-15 World Cup		

Adapted from: http://www.ibsf.org/en/tracks. (Federation, 2016a) And from: http://www.ibsf.org/en/races-results. (Federation, 2016f)

Subjects

A separate subject pool of up to 20 bobsled teams of 2 or 4 athletes is used for each analysis, though there is much overlap from race to race. All data used is pre-existing publicly available data on http://www.ibsf.org/en/races-results and the East Tennessee State University Institutional Review Board exempted the study from formal human subjects review for this reason.

Data Collection

All data was gathered from http://www.ibsf.org/en/races-results for the 2014-15 and 2015-16 seasons and compiled using Microsoft Excel (Microsoft, Redmond, WA). All statistical analysis and chart creation was also carried out using MS Excel and the "Data Analysis" package therein. Start times, finish times, start velocities, and IBSF-reported elapsed times at intermediate locations along each track were collected. Further, timing eye distances for each track were collected from a USABS national team coach. For the 2014-15 season only, split times between timing eyes were calculated by subtracting IBSF elapsed times from the subsequent elapsed time.

Statistical Analysis

All statistical analyses were carried out using Microsoft Excel 2017 (Redmond, WA). Start time, start velocity and finish times were each assessed for their reliability using paired sample t-tests and intraclass correlations (ICC). For both the 2014-15 and 2015-16 seasons, within each competition of 2- and 4-man bobsled, for each track, linear regressions between start time and start velocity, start time and finish time, and start velocity and finish time were carried out and R^2 are reported. Correlational analyses were also run between start time and start velocity and each time interval between subsequent timing eyes for all tracks in the 2014-15 season.

RESULTS

Intraclass correlational analysis between heat 1 and heat 2 start times of all top 20 sleds within all races resulted in all but two races exhibiting higher than r = .80 and all but five races exhibiting higher than r = .90, with an overall ICC average for all races of r = .94, indicating that most races had stable start time data. Notably, start time ICC between heats 1 and 2 for both the 4-man races taking place in Park City in 2015-16, during which heavy snowfall occurred, averaged r = .64. The only other examples of ICC's under r = .90 were the 4-man bobsled races in St. Moritz, and Altenberg in the 2015-16 season and the 2-man bobsled race in Konigssee

2014-15 season. The highest ICC's for a given location were in Sochi, in the 2014-15 season, averaging r = .98.

When comparing differences between average push time between heats, it was more common for the second heat average to differ from the first heat average push time than it was for the ICC to be low. There exist 10 instances of the second heat differing significantly ($p < .05$) from the first heat, only two of which indicated that the second heat was slower on average than the first heat. On average, of the tracks that did differ significantly, the average difference from the first heat was only .015 seconds. Reliability analysis of start times indicate that start time data is generally reliable with regard to team rank order, but less reliable as far as average push start time from heat to heat is concerned.

Start velocity measurement presented lower reliability than start time. ICC's revealed nine races where $r < .80$ and two races (2014-15 2-Man Konigssee and 2015-16 4-Man Park City) with no relationship between heat 1 and 2 start velocities ($-.25 < r < .25$). The average ICC for the two seasons was r = .80, indicating relatively poor rank order reliability between heats for start velocity, compared to start time.

T-tests revealed that roughly half of all races (14 of 32) had mean differences in start velocity from heat to heat. The largest differences in average velocity for all sleds between heats within a race was .9 km/hr. Unlike start time, where more often heat two was faster than heat one within a race, start velocity showed no such clear trend. Start velocity measurements tend to be less reliable in both heat average differences and rank order difference based on the results of the t-tests and ICC analyses.

Even given the relatively low reliability of start velocity, four-man start time predicted greater than 70% of the variability in start velocity on all tracks in the 2014-15 season except

Calgary and La Plagne and on all tracks in the 2015-16 season except one of the races in Park City and Altenberg. These data can be visualized in Figures 3.1 and 3.2. Altenberg in the 2015-16 season expressed the only non-significant relationship between start time and start velocity among 4-man races spanning two World Cup seasons from 2014 to 2016.

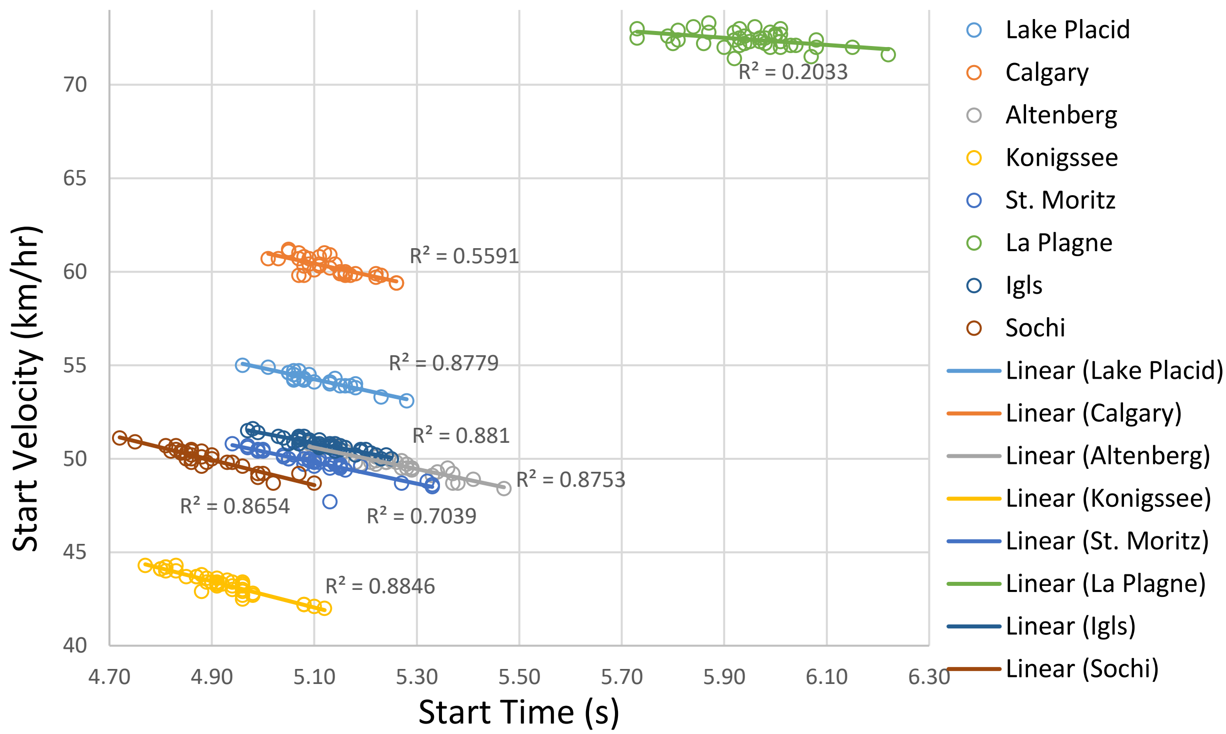

Figure 3.1. 2014-15 BMW IBSF World Cup 4-Man Bobsled start times vs. start velocities. Linear regressions are presented for each track and R^2 values are presented alongside the respective datasets.

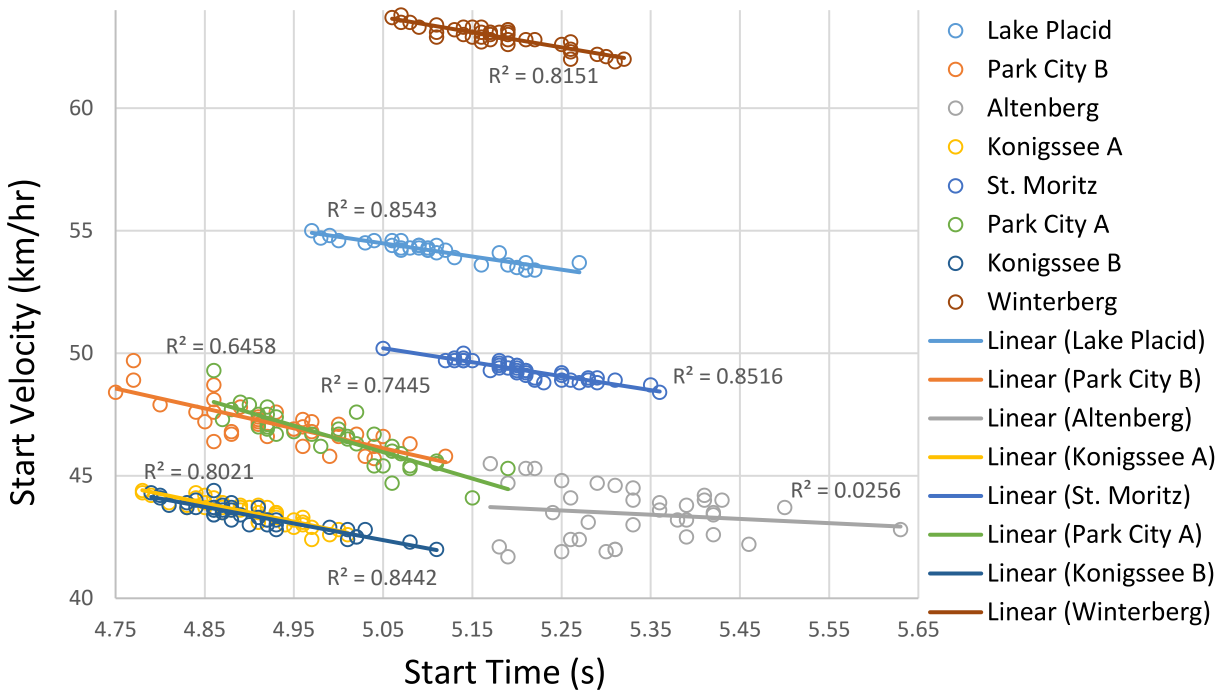

Figure 3.2. 2015-16 BMW IBSF World Cup 4-Man Bobsled start times vs. start velocities. Linear regressions are presented for each track and R^2 values are presented alongside the respective datasets.

Two man start time similarly predicted greater than 70% of the start velocity variability in all races (see Figure 3.3) except La Plagne and Konigssee in 2014-15 World Cup competition. The first Whistler race and Altenberg World Cup 2-Man bobsled were the only two instances where the $R^2 < .70$ for the 2015-16 season.

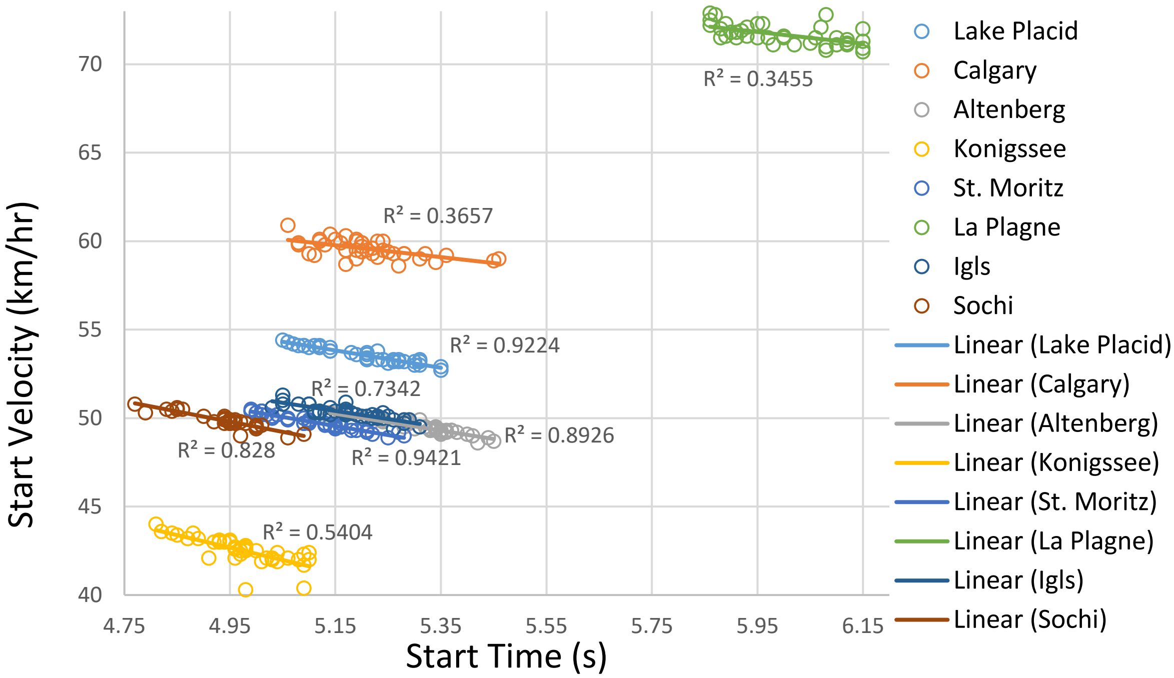

Figure 3.3. 2014-15 BMW IBSF World Cup 2-Man Bobsled start times vs. start velocities. Linear regressions are presented for each track and R^2 values are presented alongside the respective datasets.

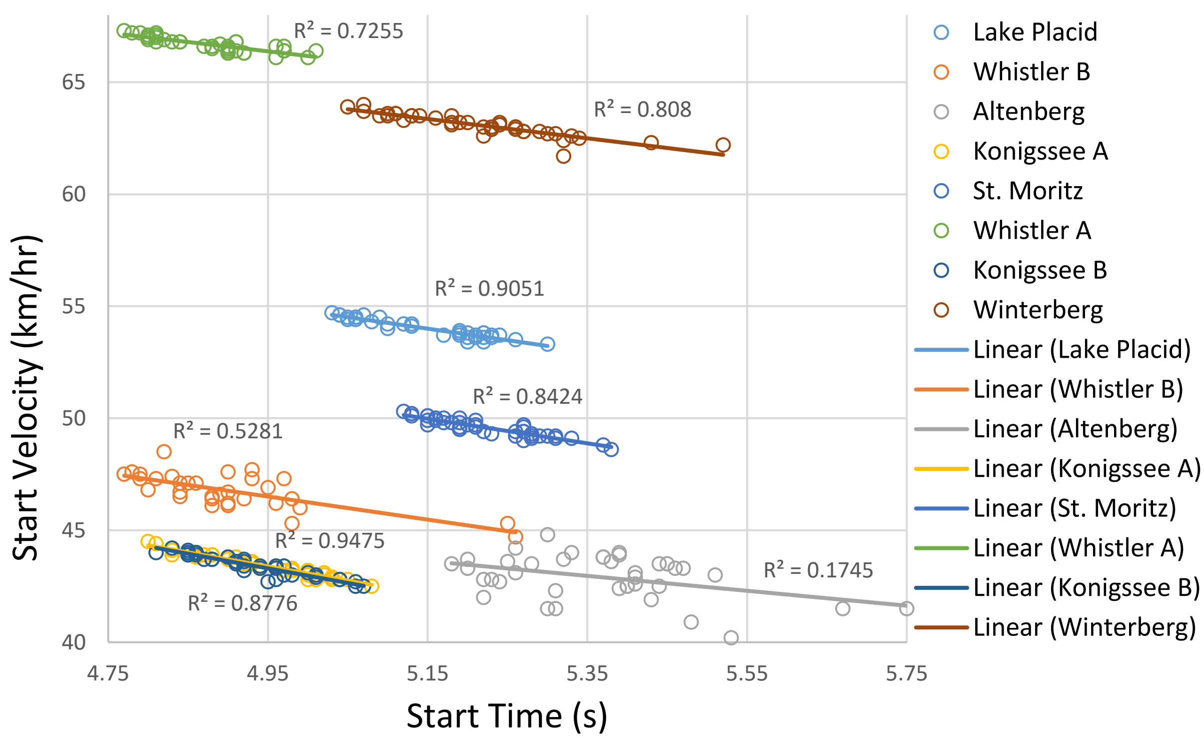

Figure 3.4. 2015-16 BMW IBSF World Cup 2-Man Bobsled start times vs. start velocities. Linear regressions are presented for each track and R^2 values are presented alongside the respective datasets.

In 2014-15 World Cup 4-Man Bobsled competition, start time predicted 28% or more of finish time in all races, with a high of greater than 71% of variation being predicted in Sochi. All regressions were significant ($p < .05$) and each specific R^2 value is presented in Figure 3.5. In the 2015-16 4-Man season 21-69% of the variability of finish time was predicted by start time, depending on the track and race, all of which can be visualized in Figure 3.6.

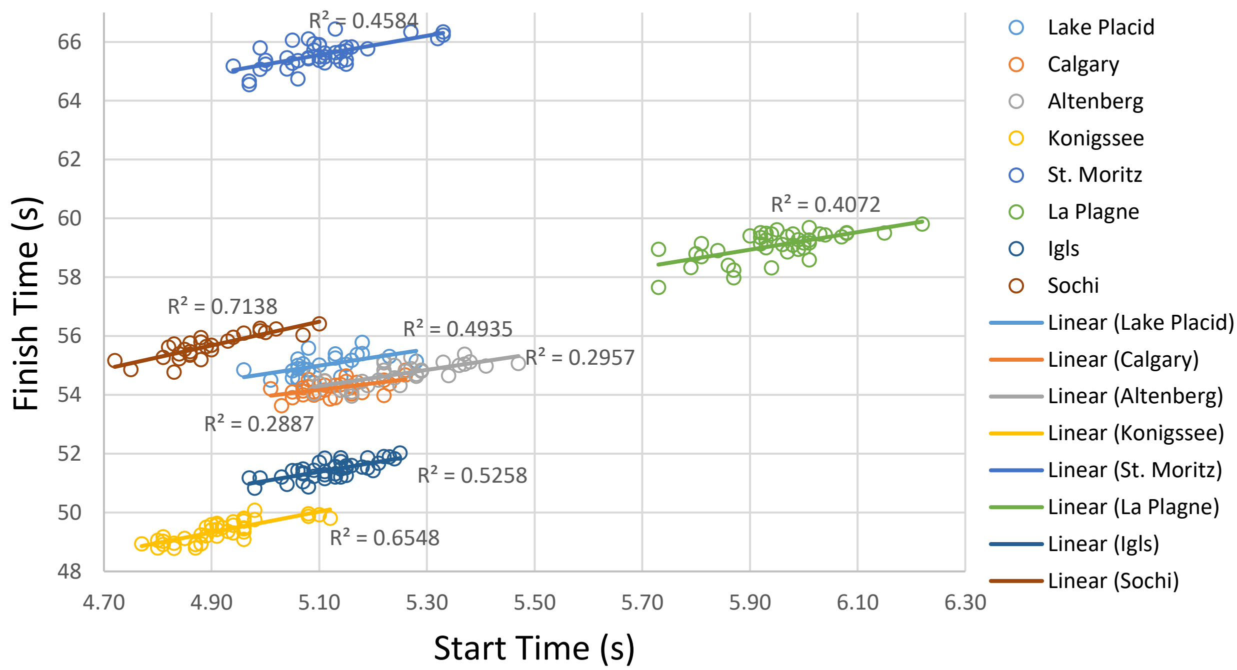

Figure 3.5. 2014-15 BMW IBSF World Cup 4-Man Bobsled start times vs. finish times. Linear regressions are presented for each track and R^2 values are presented alongside the respective datasets.

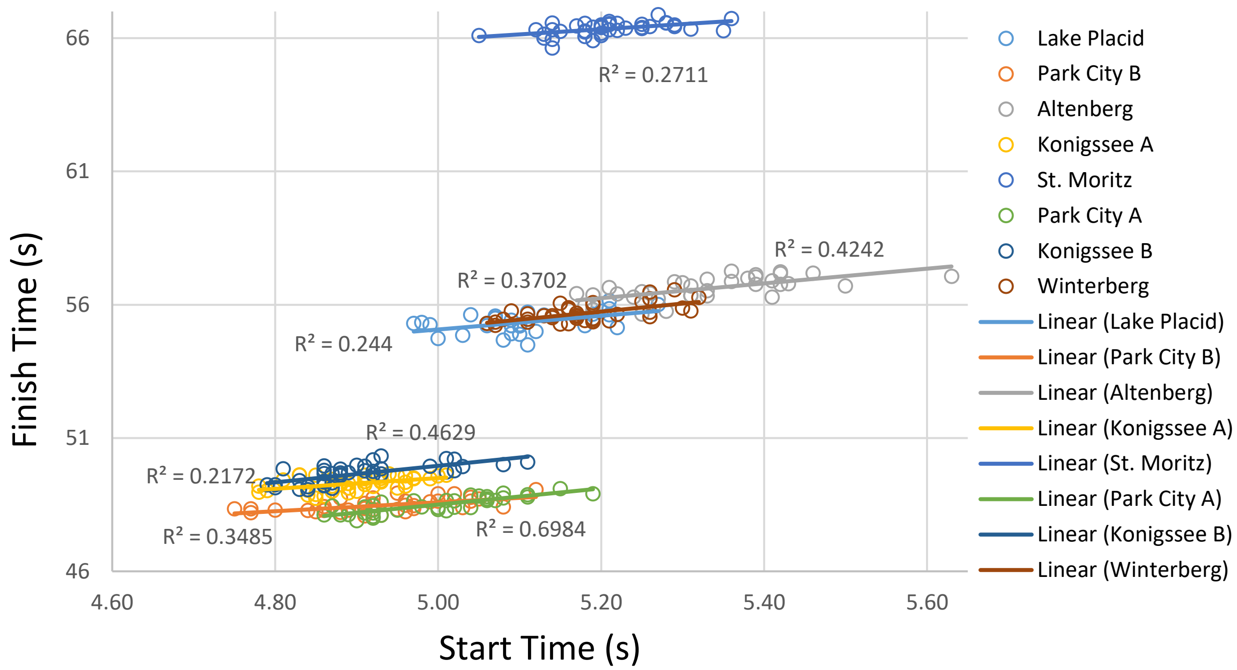

Figure 3.6. 2015-16 BMW IBSF World Cup 4-Man Bobsled start times vs. finish times. Linear regressions are presented for each track and R^2 values are presented alongside the respective datasets.

In the 2014-15 World Cup 2-Man Bobsled season, start time predicted a statistically significant portion of the variability in finish time in all the races, and in all but La Plagne, more than 30% of the finish time variability was predicted by start time. The highest percentage of variability in finish time predicted by start time over each of the two seasons was in Calgary in the 2014-15 season ($R^2 = .6945$, $p < .01$) and in Lake Placid in the 2015-16 ($R^2 = .6811$, $p < .01$).

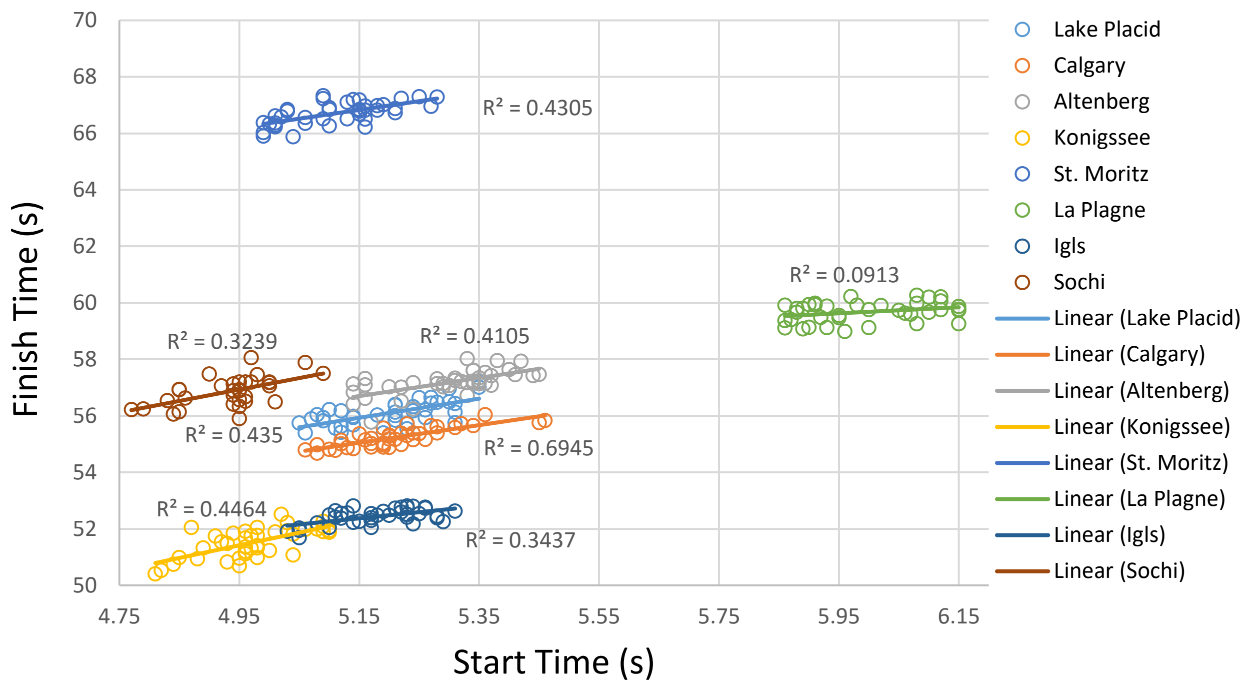

Figure 3.7. 2014-15 BMW IBSF World Cup 2-Man Bobsled start times vs. finish times. Linear regressions are presented for each track and R^2 values are presented alongside the respective datasets.

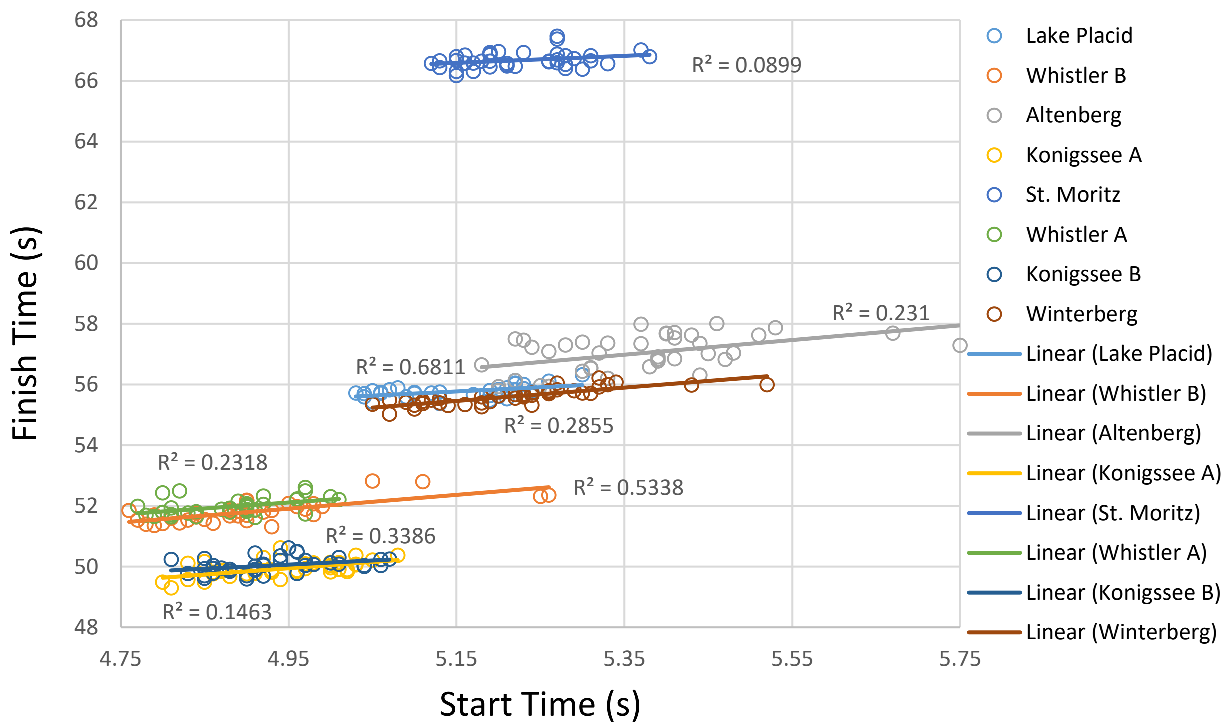

Figure 3.8. 2015-16 BMW IBSF World Cup 2-Man Bobsled start times vs. finish times. Linear regressions are presented for each track and R^2 values are presented alongside the respective datasets.

Start velocity also predicted a statistically significant ($p < .05$) portion of finish time in all races in both seasons, except the 4-man bobsled race in Altenberg in the 2015-16 season. In 4-man World Cup races, the highest relationship of start velocity to finish time was in Sochi in the 2014-15 season ($R^2 = .7764$, $p < .001$) and in 2-man World Cup races, Winterberg ranked highest ($R^2 = .8031$, $p < .001$).

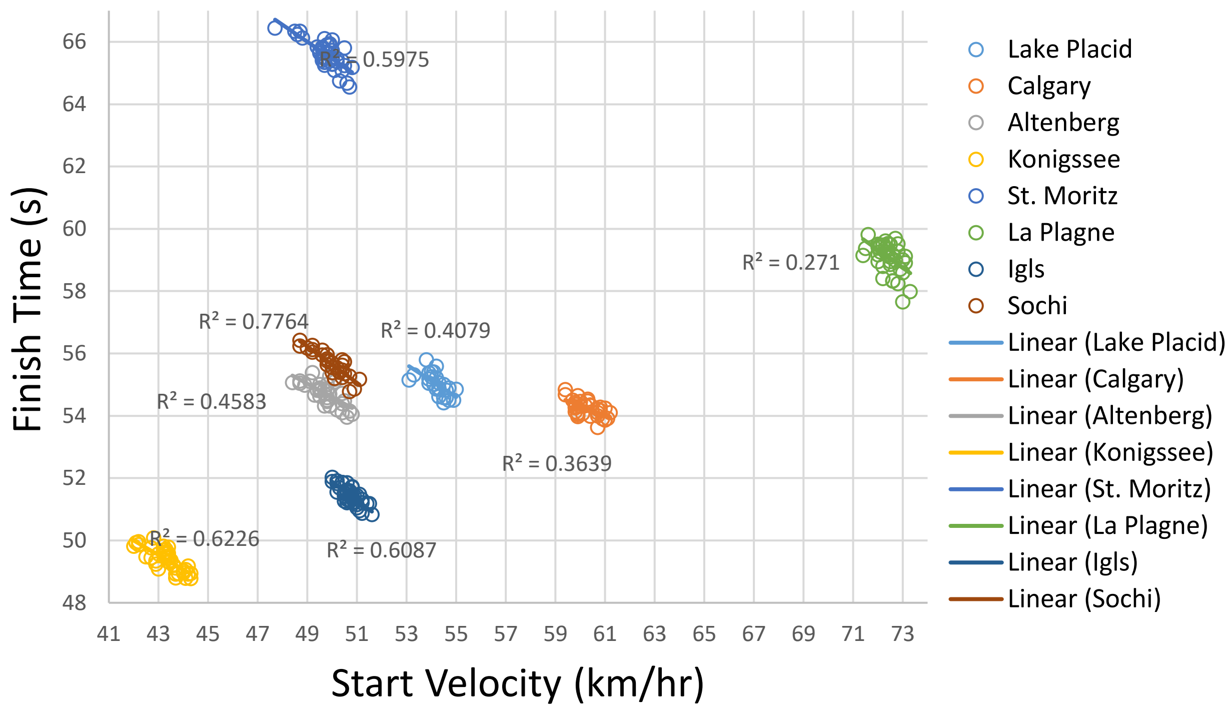

Figure 3.9. 2014-15 BMW IBSF World Cup 4-Man Bobsled start velocities vs. finish times. Linear regressions are presented for each track and R^2 values are presented alongside the respective datasets.

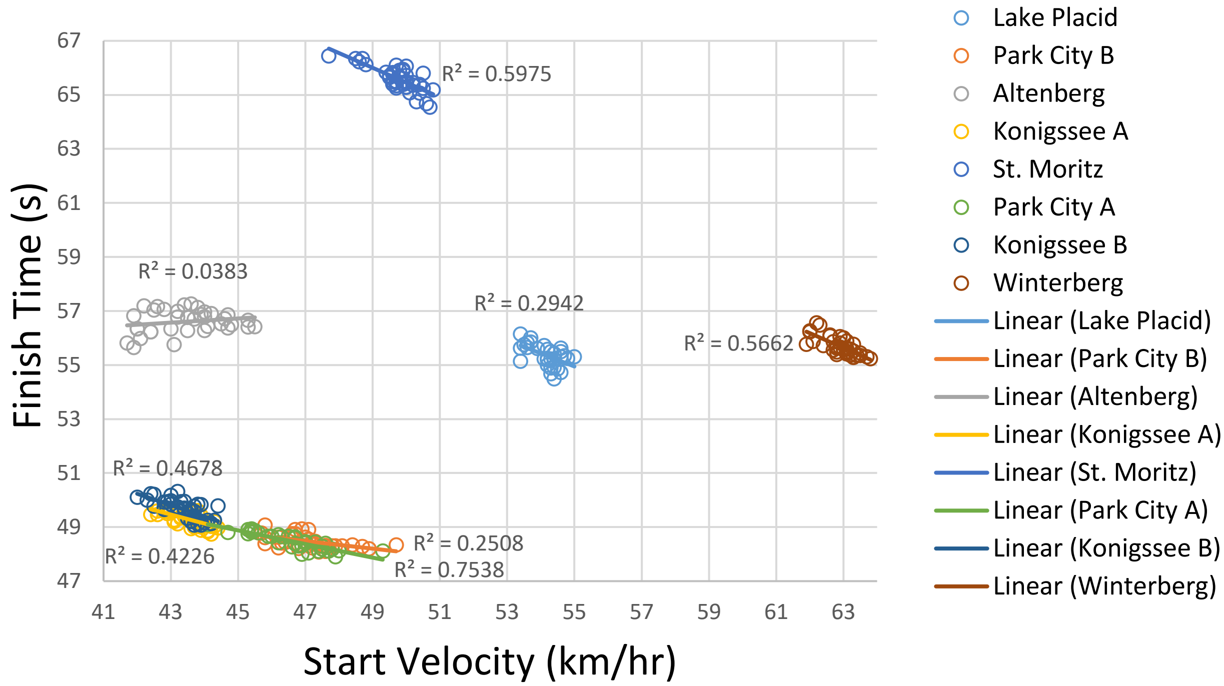

Figure 3.10. 2015-16 BMW IBSF World Cup 4-Man Bobsled start velocities vs. finish times. Linear regressions are presented for each track and R^2 values are presented alongside the respective datasets.

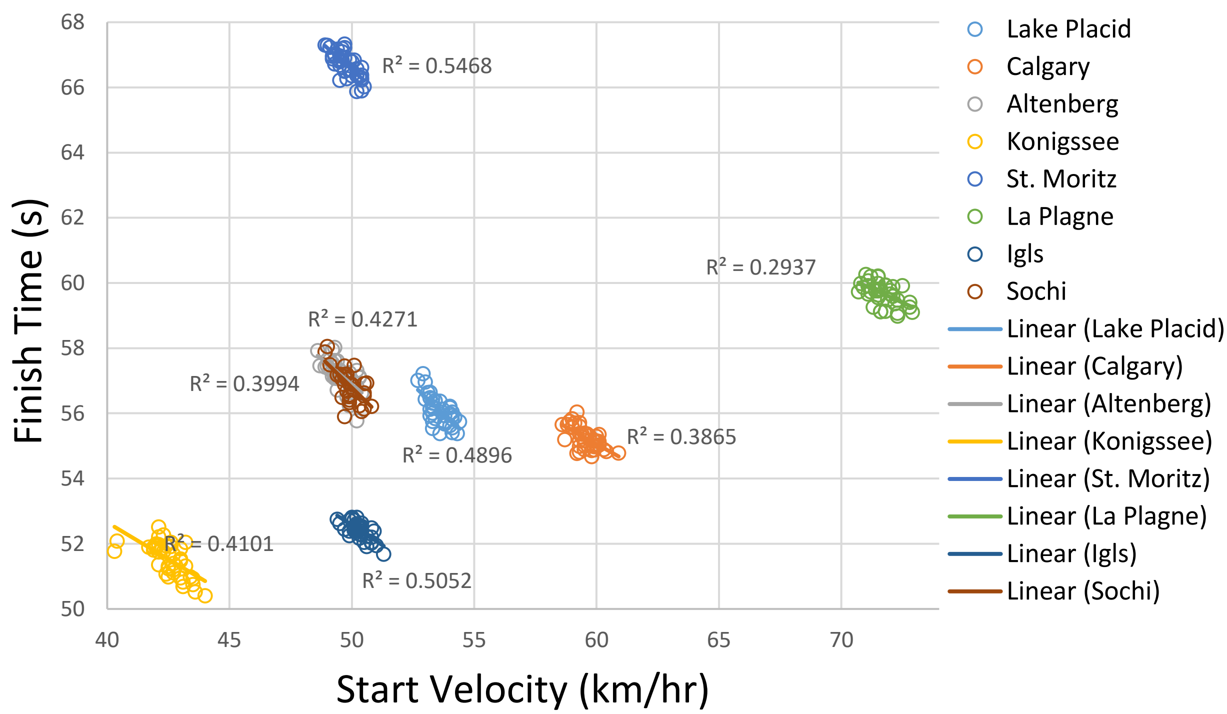

Figure 3.11. 2014-15 BMW IBSF World Cup 2-Man Bobsled start velocities vs. finish times. Linear regressions are presented for each track and R^2 values are presented alongside the respective datasets.

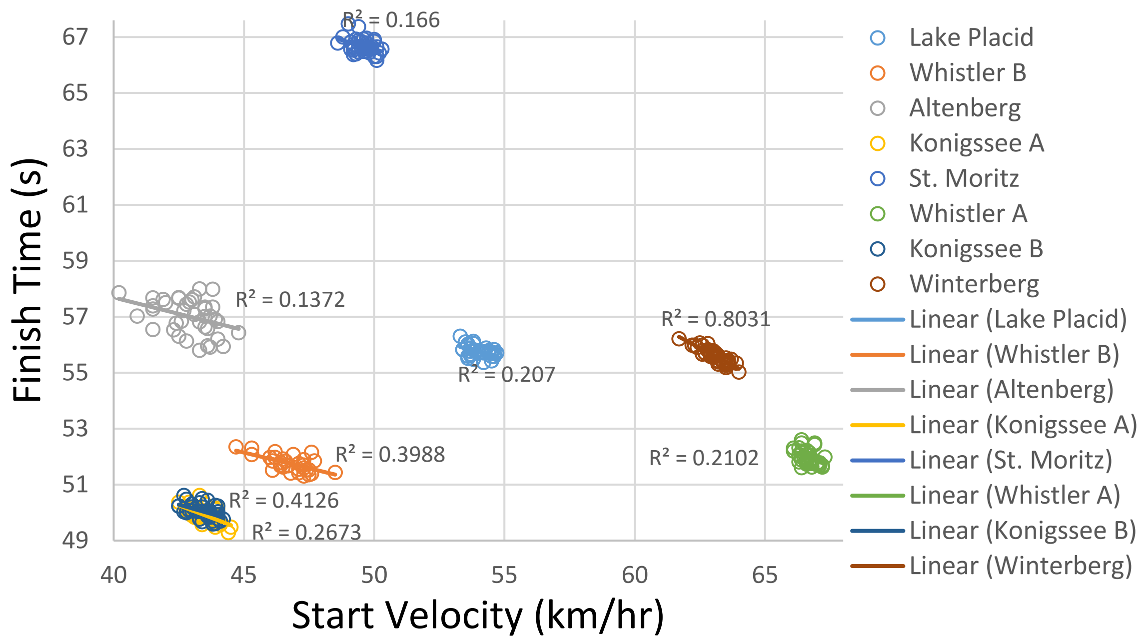

Figure 3.12. 2015-16 BMW IBSF World Cup 2-Man Bobsled start velocities vs. finish times. Linear regressions are presented for each track and R^2 values are presented alongside the respective datasets.

The average R^2 value for start time, predicting finish time for all tracks in 2- and 4-man bobsled combined is .39 with no meaningful difference between disciplines. The start velocity, even with its lower reliability, predicted a slightly larger amount of the variability in finish time ($R^2 = .43$), on average, across disciplines and tracks.

At 700 m from the start block, no track analyzed displays a correlation of greater than r = .50, whereas over the first 400 m of more than half the bobsled tracks where velocity is collected reliably (ie. not Calgary and La Plagne) the relationship of both start time and start velocity is above r = .60 and within the first 200 m of track is often above r = .85. Split-by-split correlations to start time or start velocity for all tracks in the 2014-15 season for both 2- and 4-man bobsled are presented in Figures 3.13, 3.14, 3.15, and 3.16. These data are presented visually for the purpose of understanding the diminishing rate of the relationship of the start over the course of each bobsled track.

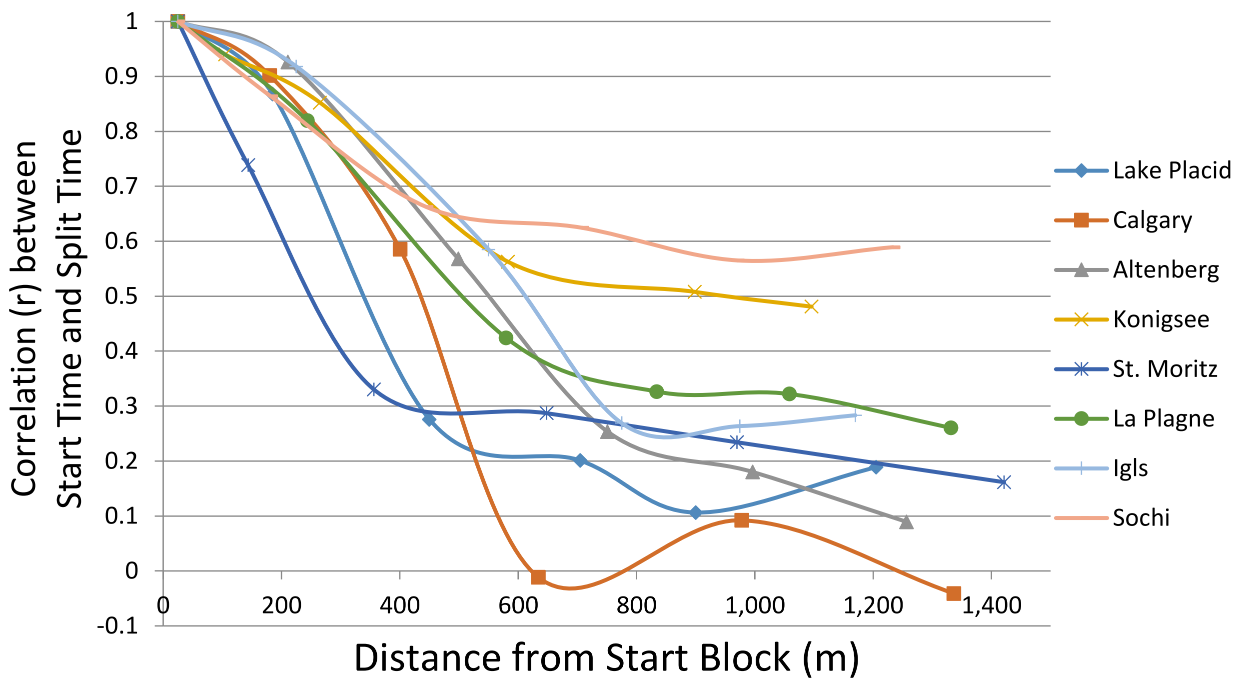

Figure 3.13. Correlations between Split Time and Start Time presented by distance from the starting block for visual representation of the diminishing relationship between start time and subsequent split times. Data from 2014-15 World Cup 4-Man Bobsled Season.

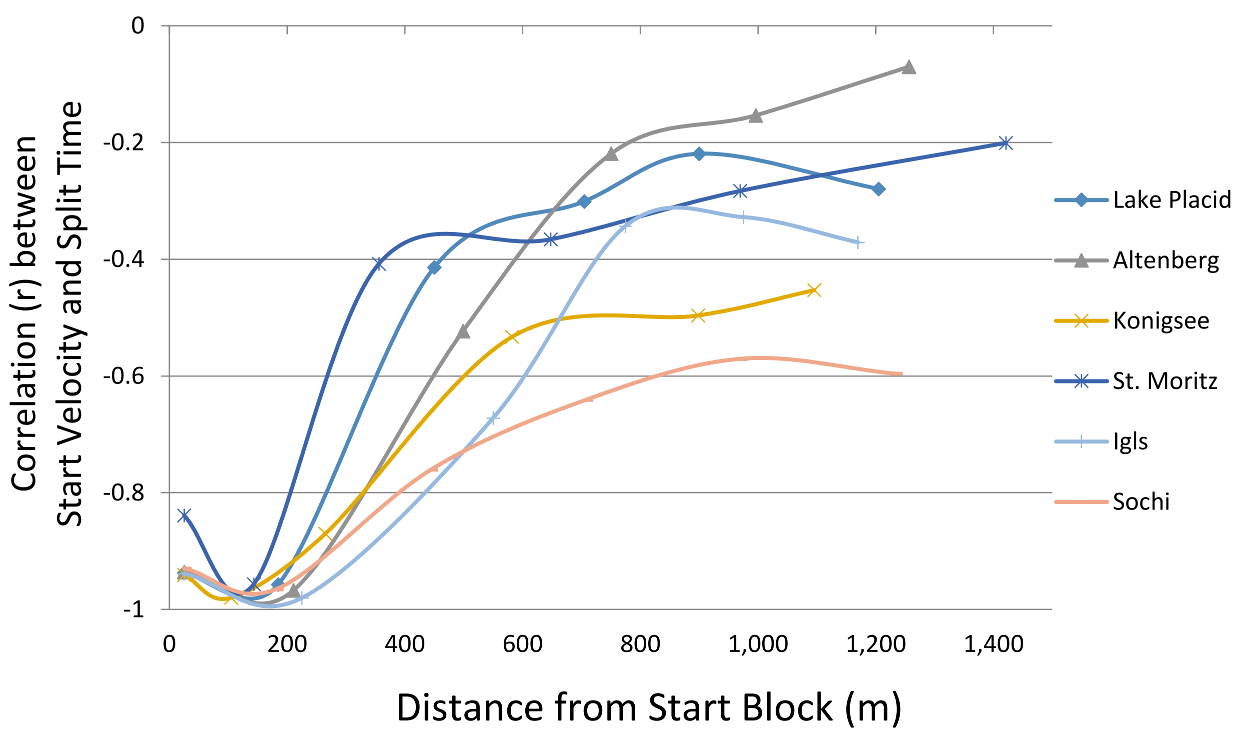

Figure 3.14. Correlations between Split Time and Start Velocity presented by distance from the starting block for visual representation of the diminishing relationship between start time and subsequent split times. Data from 2014-15 World Cup 4-Man Bobsled Season.

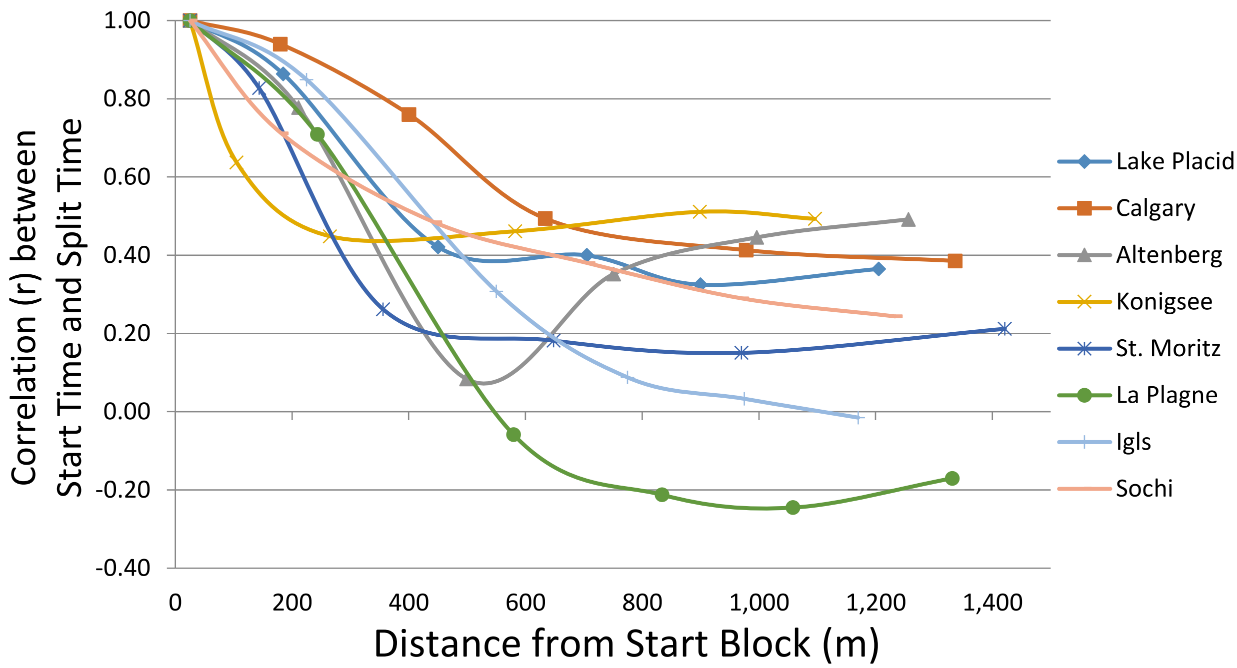

Figure 3.15. Correlations between Split Time and Start Time presented by distance from the starting block for visual representation of the diminishing relationship between start time and subsequent split times. Data from 2014-15 World Cup 2-Man Bobsled Season.

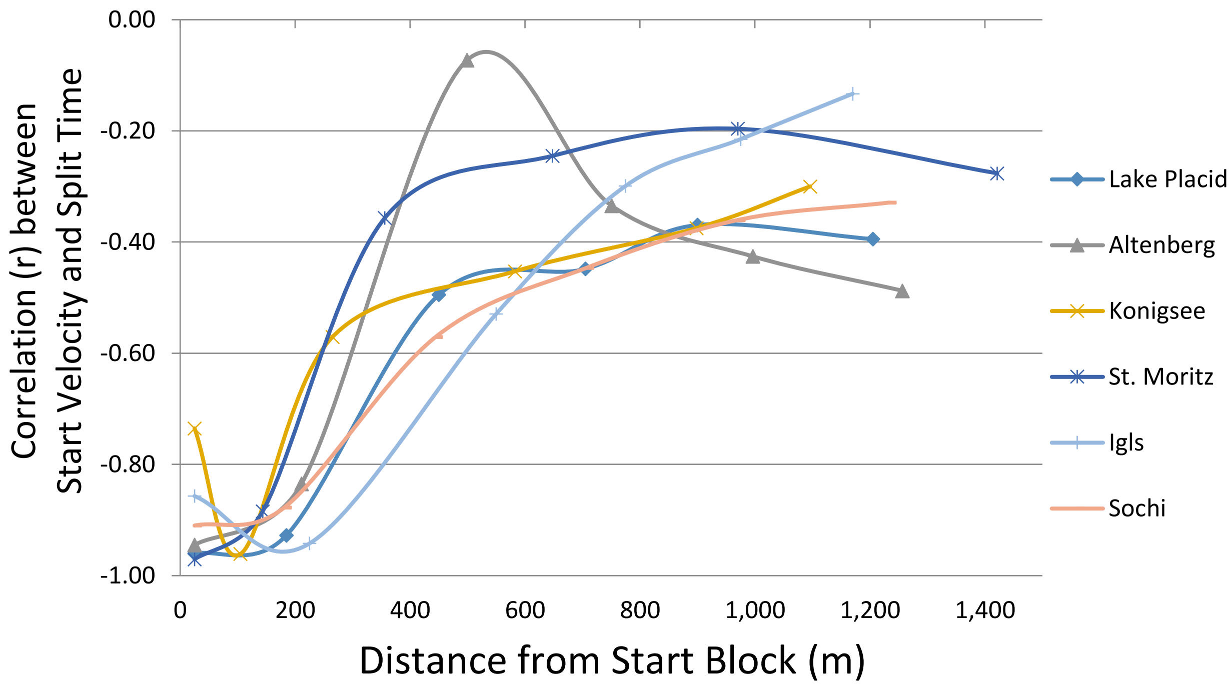

Figure 3.16. Correlations between Split Time and Start Velocity presented by distance from the starting block for visual representation of the diminishing relationship between start time and subsequent split times. Data from 2014-15 World Cup 2-Man Bobsled Season.

DISCUSSION

Reliability analysis showed much higher reliability of bobsled push start time data than start velocity data. This is likely caused by the uniformity and standardization of start time measurement across all bobsled tracks internationally (Federation, 2016e). Start time is measured 65 m from the start block and start velocity may be measured in a track-specific manner. In some cases, sequential timing eyes closely placed in series are used for an instantaneous velocity estimate. On other tracks such as Calgary and La Plagne these timing eyes may be a much larger distance apart, separated by one or more turns. This is likely to reduce the reliability and utility of the velocity measurement as a measure of start performance, because the grooves typically end shortly before the 65-m timing eye, opening the bobsled-crew system to more outside influence. Any track distance after that timing eye increases chance of outside influence like driver error or materials or aerodynamics to begin to play a meaningful role in sled velocity. Given that La Plagne and Calgary present start velocity data (Figure 3.1 and 3.3) that is more than 10 km/hr faster than the average of all the other tracks, those two start ramps are two of the longest and flattest in the world, and the relationship to start time is diminished on both tracks, it is likely that the timing eyes or means of velocity measurement are meaningfully down-track.

The first 2015-16 Whistler 2-man (Whistler A, in Figure 3.4) and Winterberg 2-Man (also Figure 3.4) bobsled races both present similarly to the Calgary and La Plagne data of the previous season, in that their reported start velocities are faster than are possible at 65 m from the start block, and the velocity relationship to start time is diminished. The second Whistler 2-man race (Whistler B, in Figure 3.4) also exhibits low reliability and relatively low relationship with start time. This low reliability and lowered relationship of start velocity to start time lends further credence to the idea that if start velocities were measured more accurately or measured more temporally near to the cessation of the start zone, the relationship between start time and start velocity would be consistently higher than is currently reported at the aforementioned tracks.

The velocity data from Altenberg and Park City are especially scattered and not reliable. This resulted in a relatively low relationship between start velocity and start time, even though it appears that start velocity was taken nearly instantaneously near the 65-m timing eye because of the relatively low start velocities that are in alignment with what is attainable within a 65-m start ramp. Despite the generally lower reliability of start velocity, start time widely showed a very high ability to predict start velocity, because start time and velocity are measured so close together physically and temporally in Park City and Altenberg. Races where snowfall wasn't present and where start velocity is measured at or very near the 65-m timing eyes tend to exhibit higher reliability of velocity data and higher relationships between start time and start velocity. No other studies have examined at this relationship directly before.

It was expected that push time would have some relationship with finish time if for no other reason than the first 50 m of the timed portion of the tracks take approximately 10% of the elapsed time to finish the approximately one-mile tracks (see Table 3.1 in the Methods section for more detail on track length and elapsed time taken to travel the first 50 m, as a percent of finish time). Further, it was anticipated that start time would have a relationship with finish time because start time has historically been used as a proxy for how fast the sled would be entering the driving portion of the track, and a common phrase among bobsled coaches and pilots: "a tenth of a second at the top is three tenths of a second at the finish."

Indeed, there is a stronger than 10% predictive ability of the start time to finish time in all but the La Plagne 2-Man race in the 2014-15 season and the St. Moritz 2-Man race in the 2015-16 season. The average predictive ability of both start time and velocity were essentially the same at 39% and 43% of the variability of finish time being predicted by each, respectively. It is possible that the reason for the slightly greater relationship overall between start velocity and finish time its inflation due to the measurement of velocity slightly lower down-track on a number of tracks. Morlock and Zatsiorski (1989) showed that as the sled travels farther from the start, both the velocity and the elapsed time become more strongly correlated with finish time. In Calgary in particular they identified one curve in the upper half of the track that determined much of the outcome of the race, and it is possible that other tracks have no such critical point where the relationship between split times and finish time dramatically increases (Morlock & Zatsiorsky, 1989). This more steady increase in relationship between sled velocity or split times and finish time as the sled travels farther from the start is in alignment with the findings of a study of the 1994 Lillehammer Winter Games, and lends credence to the idea that the velocity predictive ability of finish time presented herein may be inflated due to inconsistent and later velocity measurement (Brüggemann et al., 1997).

It is possible that the predictive ability of both start time and velocity are also artificially inflated because of the tendency for the nations to put their best brakemen with their best pilots in both 2- and 4-man bobsled. Further, often the most research and best materials also go into the known leading pilots within a nation's program. This may be causing an overstatement of the predictive ability of the push if all driving skills were held equal. That is, the effective importance of the push phase may not be as critical as the ~40% reported for both start time and velocity, while it still is predictive of race outcomes from a purely observational standpoint.

This stacking the deck effect may be seen in the results of the 2014-15 Sochi races. Previously researchers have identified that longer more technical tracks generally have weaker start-finish relationships, and this would be expected of a track like Sochi, which has relatively novel technical components, was relatively new to many pilots in the 2014-15 season, and is a longer-than-average track (Bullock et al., 2008). Although a lower start time to finish time relationship might have been expected at Sochi because of these factors, because there was prize money available and it was the final World Cup race of the season before the 2015 World Championships, the nations may have put together their best crews and materials with their best pilots to give higher probability of victory. Indeed, there was a very large predictive ($R^2 > .70$, $p < .001$) ability of start time to finish time in the 4-man Sochi race. This could have potentially occurred by a magnifying of the statistical relationship between start time and finish time with no practically meaningful increase in the effect of start time on the rate at which the sled covered the rest of the track.

Velocity measurement standardization could lead to increased utility of the measurement for coaches and national team selection committees, as well as pilots and crews. As of right now, push crews may be judged incorrectly, either because of early-track driving skill or mishaps by the pilot that either positively or negatively affect the sled-crew velocity before the measurement is taken on the following tracks: Winterberg, Whistler, La Plagne, Calgary.

The data in the present study agree with the literature on skeleton racing at the World Cup level. Start time was previously found to be most associated with finish time on "pure push tracks" as opposed to more "driving oriented tracks" as rated by professionals in the sport.

To elucidate the relationship and its strength over the course of various tracks, correlations between start time and subsequent split times are presented in Figures 3.9, 3.10, 3.11, and 3.12. It is apparent that the strongest relationship exists in the top quarter of the track. This is in alignment with the physics of the scenario which presents rapidly increasing friction and drag as velocity increases, (Walker, 2010) as well as increased opportunity for driver error. These things, all taken together, reduce the relationship of the start variables similarly over the course of the first half of each of the tracks. The plateauing of the relationship between the start time and velocity and discrete split times beyond 50% of the track length may be more indicative of the pairing of top pilots and materials with top crews of push athletes, as opposed to some amount of velocity maintenance from the start of the race.

PRACTICAL APPLICATION

As a popular Olympic sport, bobsled success is often determined by small variations in finish time, making it imperative that the push start and its effects on the rest of the race are more fully understood. The present study identified that the relationship between start time and start velocity quickly wanes during the first half of the track. Given the opportunity to build a lead or vice versa at the beginning of the bobsled race, based on the quality of the push start, coaches of this power sport should pay special attention to both velocity and start time and interpret time losses or advantages during the upper portion of the track through the lens of these variables.

Interpretation of velocity and split data from the lower two thirds of the track should be interpreted with caution with regard to start effects because it appears that other factors, outside of the push start, are largely responsible for the variation seen in these down-track split times.

Start velocity data should also be interpreted with caution with respect to the pushing and loading ability of the athletes, especially on tracks where the velocity reported is more than 55 km/hr because of the relatively low reliability if the data and the likelihood of outside influence other than the push athletes pushing and loading paradigm. It is suggested that the IBSF standardize all velocity measurement on all tracks and report it with the same level of accuracy and reliability as is found with start time data.

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CHAPTER 4

THE BOBSLED PUSH START: FIELD-TESTING CORRELATES FOR BOBSLED PUSHING-PERFORMANCE

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THE BOBSLED PUSH START: FIELD-TESTING CORRELATES FOR BOBSLED-PUSHING PERFORMANCE

Abstract

Purpose: The purpose of the present study was to investigate the validity of various field testing and other characteristics like athlete body weight for use as indicators of bobsled pushing performance on the Olympic Training Center push track in Lake Placid, NY. **Methods:** All publicly available data from the 2014 and 2015 USABS, Bobsled Preliminary Push Championships and National Push Championships were analyzed, including 16-24 subjects per competition. Correlations within year were calculated between sum of push times at preliminary push championships and all combine variables tested in the USABS 8-item combine: sprints of 15 m, 30 m, 60 m, 30-m fly, standing broad jump, underhand shot toss, one repetition maximum power clean, and three repetition maximum back squat. **Results:** Measures of strength and power showed strongest relationships with pushing ability and the most discriminative ability between top level push athletes. Measures of sprint speed and acceleration ability also strongly correlated to push performance among wide ranges of push athlete skill level but largely failed to significantly discriminate between top level push athletes. **Conclusions:** Measures of strength and power appear to be more predictive of bobsled pushing performance than measures of speed or acceleration, especially at the highest level of the sport in the USA. Given further research, some combination of those might predict sled-pushing performance better, using a multiple regression style analysis. For sled-pushing performance to be better-predicted by the combine variables and thereby used as a valid measure during talent identification or training monitoring, increased standardization of technique in power- and strength-testing is necessary.

Key Words: *talent ID, athlete monitoring, speed, strength, resisted sprints, power*

INTRODUCTION

The Winter Olympics and are the largest single winter sport gathering in the world, and are hosted every four years with nearly 100 nations competing. Since 4-man bobsledding became a part of the Winter Olympics in 1924, and 2-man bobsled joined in 1932, each have progressed with all the technological developments of the 20th and 21st centuries (Federation, 2016b). Some of these technological developments have included sled design, track safety, and training methodology of athletes (Federation, 2016b).

It is widely accepted by fans and those within the sport alike that the start phase of a bobsled race is a critical determinant of success in the race overall. Several studies have elucidated the relationship between the push start and the finish time in sliding sports, and specifically in 2- and 4-man bobsled (Brüggemann et al., 1997; Morlock & Zatsiorsky, 1989). An often quoted saying within the sport is that one tenth of a second difference at the start may become three tenths of one second by the bottom of the track. Statistically, the relationship between start time and finish time is usually in the range of .4 to .8, with the magnitude of relationship being largely track-dependent (Brüggemann et al., 1997; Harrison et al., 2017; Morlock & Zatsiorsky, 1989).

Given the importance of the push start phase in bobsled racing, it is necessary to determine what athletic characteristics are required for success in bobsled pushing performance. There has been thorough examination of the various predictors of sprint ability and there exists a growing body of research on resisted sprinting (Hrysomallis, 2012). In most well-designed studies, absolute strength, relative strength in compound movements, and multi-joint measures of power output are correlated with sprints speed (Baker & Nance, 1999; Comfort et al., 2012; Comfort et al., 2014; Cronin & Hansen, 2005; Sleivert & Taingahue, 2004). Many of the same variables that are predictive of sprinting performance may be predictive of resisted sprint performance, with perhaps a shift towards greater demands on the strength and power of the athlete, given that stronger athletes tend to move with higher velocities and power outputs against increasingly heavier loads (Haun et al., 2017; Kraska, Ramsey, Gregory, et al., 2009). However, the predictors of resisted sprinting ability have been only sparsely investigated (Osbeck et al., 1996). Several studies have examined bobsled athletes for their physical characteristics, but most have simply compared bobsled athletes to other groups of athletes and found that generally bobsledders are relatively large and powerful, and possess mesomorph phenotypes (Kirkendall & Street, 1986; Koutedakis et al., 1998; Stanula et al., 2013).

Only one study has examined, in detail, physical abilities of bobsled athletes over a combine battery that is similar to the Team USA combine currently used for talent identification and athlete monitoring (Osbeck et al., 1996). The current talent identification process in for Team USA Bobsled athletes is begun with a combine, and subsequently one or more push championship events where prospective athletes, or prospective and returning national team athletes, have an opportunity to push a bobsled alone, for time, against other competitors on a rubberized bobsled push track. These push championships are the final official indicator through which bobsled pilots make their selection of their crews for season, and although no research has been carried out on the topic, it is assumed by coach and athlete alike that there is a strong, valid and reliable relationship between push championship performance and pushing ability on ice in actual bobsled races. Osbeck and colleagues (1996) identified that speed and power measurements were highly predictive of bobsled push athlete performance in their population sample, but given the inclusion of exceptionally low-ability athletes in their sample, the generalizability to top-level Team USA athletes or elite push athletes worldwide is low.

There is a need for elucidation of physical characteristics and performance metrics that can be used to validly identify bobsled push athlete potential, and for use as valid athlete monitoring and testing tools by strength and conditioning practitioners, coaches, and selection committees in the sport of bobsled. The present study examines the relationship of various strength, power, and speed metrics to push championship times, to clarify the direction, magnitude, and meaningfulness of these relationships. To further clarify the meaningfulness of various strength, power and speed metrics in discriminating between top push athletes, athletes were stratified into groups based on finish rank, and differences in the same strength, power and speed metrics are examined for their differences between groups.

METHODS

Experimental Approach to the Problem

Data from Preliminary and National Push Championships (PPC, NPC, respectively) in 2014 and 2015 within USA Bobsled and Skeleton (USABS), as well as combine data from the 2014 and 2015 recruiting seasons is used to investigate the relationship between several physical characteristics and push time. Physical tests included as independent variables (IV) in the analysis are as follows: 15-m, 30-m, 60-m sprints (15m, 30m, 60m, respectively), 30-m fly (30f), standing long jump (SLJ), 7.26-kg underhand shot toss (UST), one-repetition maximum (1RM) power clean (PC) or clean, and three-repetition maximum (3RM) back squat (BS). Additionally, several combinations of points from individual combine events, as outlined by USABS, including three-item combine (3-ITEM), six-item combine (6-ITEM), eight-item (8-ITEM) combine scores, and body mass and athlete age are included in the analyses. The dependent variable in all analyses was the athletes' total push time from the push championship in question.

Subjects

Four separate subject pools are used, with one subject pool arising from each of the push championships analyzed (2014 & 2015, PPC and NPC, respectively). Not all subjects' data was available, as is common to team-organized testing batteries that are not initially for the purpose of science. Any subject who had even a single independent variable reported is included in the presentation of subject data within the methods section, but further detail on subject number per analysis is presented in Table 8 in the Results section. For age and body mass data on a per championship basis for ALL athletes, refer to Table 4.1.

Table 4.1. Subjects' data from all four push championships. BM = Body mass in kilograms, Age = chronological age from birth, collected to the nearest whole year. n = subject number. Data shown are mean +/- standard deviation.

	n	BM (kg)	Age (yr)
2014 PPC	16	96.0 +/- 7.9	24.4 +/- 2.3
2014 NPC	20	95.6 +/- 7.3	25.4 +/- 2.0
2015 PPC	23	93.3 +/- 9.3	25.4 +/- 2.8
2015 NPC	24	96.2 +/- 6.0	26.5 +/- 2.8

All data used is pre-existing publicly available data on www.usabs.com and the East Tennessee State University Institutional Review Board exempted the study from formal human subjects review for this reason.

Procedures

All data was gathered from www.usabs.com, the official website of USABS. All combine data from 2014 and 2015 was compiled in Microsoft (MS) Excel (Microsoft, Redmond, Washington) for all athletes participating in any of the 2014 or 2015 PPC or NPC. All 2014 and 2015 PPC and NPC results were also compiled in MS Excel. All statistical analysis and chart creation was also carried out using MS Excel and the "Data Analysis" package therein.

Statistical Analysis

Each of the 2014 and 2015 PPC and NPC competitions total push times were used as the independent variable in all analyses. Correlational analysis can be useful in identifying potentially meaningful relationships between athlete characteristics, but can be affected dramatically by subject number, so the significance of the correlations reported herein should always be viewed considering the subject number reported for each analysis.(Altman & Krzywinski, 2015) Correlations were carried out between each dependent variable from the temporally most near combine performance to the top 10 and to all competitors' total push time at each of the four push championships analyzed. Regressions were also run for both the top 10 competitors, and separately, for all competitors, and R^2 values reported, for any dependent variable which expressed statistically significant correlation with push time for either group.

Second, push results from each of the four championships were used to split competitors into various groups as follows: top five athletes (TOP5), second five athletes (2^{ND}-5), top 10 athletes (TOP10), all but the top five athletes (NOTTOP5), all but the top 10 athletes (NOTTOP10), and the whole group (ALL). These groups were then compared for their average DV values and effect sizes between all groups were calculated. To examine statistical significance between groups, independent t-tests were carried out between all group means for all DV. Further, 95% confidence intervals were calculated for all group DV means and DV mean differences between groups.

RESULTS

The results of all correlations between each dependent variable to total push time within each push championship can be viewed in Table 4.2 alongside respective subject numbers and p-values on an analysis-by-analysis basis.

Table 4.2. Correlations between DV and push time in each of four push championships. *Italics* indicates .05 < p < .10. **Bold** indicates p < .05. **Bold and underlined** indicates p < .01.

		15m (s)			30m (s)			60m (s)			30f (s)		
	Group	n	r	p	n	r	p	n	r	p	n	r	p
2014 PPC	TOP10	9	.18	.651	9	.29	.454	9	.38	.313	9	.24	.531
	ALL	16	.63	**.009**	16	.77	**.000**	16	.70	**.003**	16	.60	**.015**
2014 NPC	TOP10	9	.33	.591	10	.07	.858	5	-.53	.359	5	-.76	.135
	ALL	23	.43	**.041**	23	.45	**.030**	13	.43	.139	13	.24	.425
2015 PPC	TOP10	10	-.31	.379	10	-.17	.647	10	.06	.869	10	.14	.707
	ALL	15	.00	.989	15	.17	.539	13	.30	.323	15	.38	.168
2015 NPC	TOP10	10	-.39	.269	10	-.17	.640	6	.35	.502	6	.24	.645
	ALL	20	.19	.425	20	.31	.191	15	.34	.222	16	.32	.221
		SBJ (m)			UST (m)			1RM Clean (kg)			1RM PC (kg)		
	Group	n	r	p	n	r	p	n	r	p	n	r	p
2014 PPC	TOP10	9	-.23	.560	9	-.29	.450	10	-.42	.232	9	-.60	*.085*
	ALL	16	-.48	*.063*	16	-.63	**.009**	15	-.67	**.006**	13	-.86	**.000**
2014 NPC	TOP10	5	-.33	.589	5	-.09	.887	9	-.13	.745	8	-.31	.462
	ALL	13	-.29	.336	13	-.50	*.079*	21	-.37	*.095*	17	-.74	**.001**
2015 PPC	TOP10	10	-.23	.518	10	-.65	**.040**	8	-.61	*.083*			
	ALL	15	-.58	**.024**	14	-.66	**.010**						
2015 NPC	TOP10	6	-.31	.555	6	-.55	.257	9	-.09	.823	9	-.09	.823
	ALL	16	-.51	**.044**	16	-.72	**.001**	18	-.48	**.044**	17	-.68	**.002**
		3RM BS (kg)			8-ITEM (points)			6-ITEM (points)			3-ITEM (points)		
	Group	n	r	p	n	r	p	n	r	p	n	r	p
2014 PPC	TOP10							9	-.37	.333	9	-.32	.406
	ALL							16	-.79	**.000**	13	-.67	**.013**
2014 NPC	TOP10							5	.34	.578	8	-.42	0.30
	ALL							16	-.66	**.005**	18	-.59	**.010**
2015 PPC	TOP10	9	.57	.108	9	-.23	.560	10	-.08	.818	9	.17	.112
	ALL							14	-.51	*.062*			
2015 NPC	TOP10	9	-.25	.513	9	-.42	.487	6	-.22	.681	9	.24	.528
	ALL	17	-.52	**.033**	17	-.62	**.017**	16	-.53	**.034**	17	-.38	.128
		BM (kg)			Age (years)								
	Group	n	r	p	n	r	p						
2014 PPC	TOP10	9	-.14	.721	9	-.44	.236						
	ALL	16	-.25	.355	16	-.48	*.061*						
2014 NPC	TOP10	9	-.39	.295	10	-.31	.377						
	ALL	21	-.53	**.013**	23	-.15	.502						
	TOP10	10	-.62	*.056*	10	.05	.882						

2015 PPC	ALL	19	-.79	**<u>.000</u>**	14	-.22	.447		
2015 NPC	TOP10	8	-.11	.798	10	-.19	.590		
	ALL	17	-.56	**.019**	24	.01	.973		

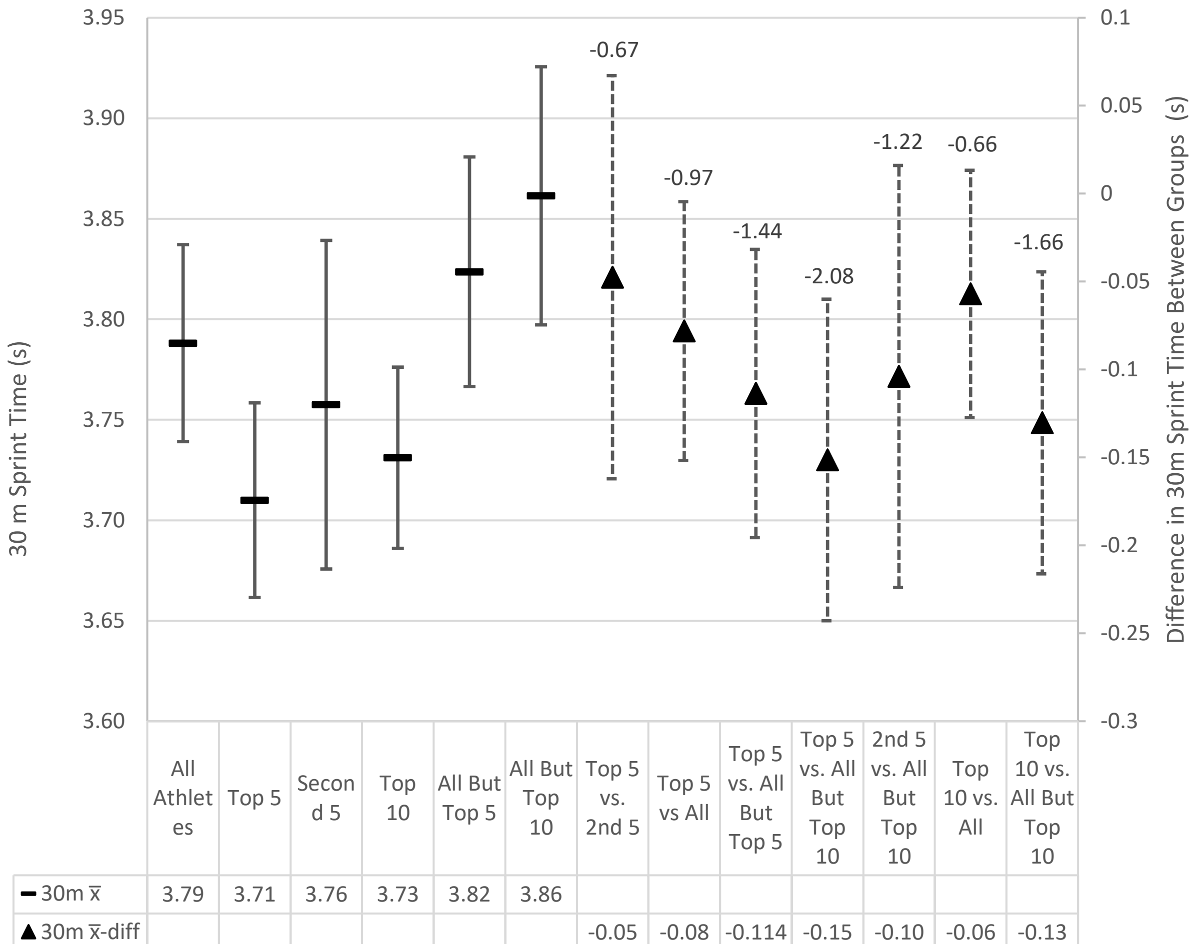


Figure 4.1. PPC 2014, 30-m sprint times for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.

Group mean comparisons and their effect sizes are presented in detail in Tables 4.3-4.6 in Appendix B. Figures 4.1, 4.2, and 4.3 depict the group mean comparisons for the 30m, UST, and 1RM PC, each displaying two or more significant differences between higher performing groups of athletes and their lower ranking counterparts. In the 2014 PPC the largest effect sizes between groups were seen between TOP5 and NOTTTOP10 for the 30m ($\Delta\bar{x}$ = -.15 s, *d* = -2.08), and between TOP5 and NOTTOP10 for the 1RM PC ($\Delta\bar{x}$ = 26.5 kg, *d* = 2.15). The strongest differentiator in the 2014 PPC between TOP5 and 2ND5 was the 1RM PC ($\Delta\bar{x}$ = 8.0 kg, *d* = 0.78).

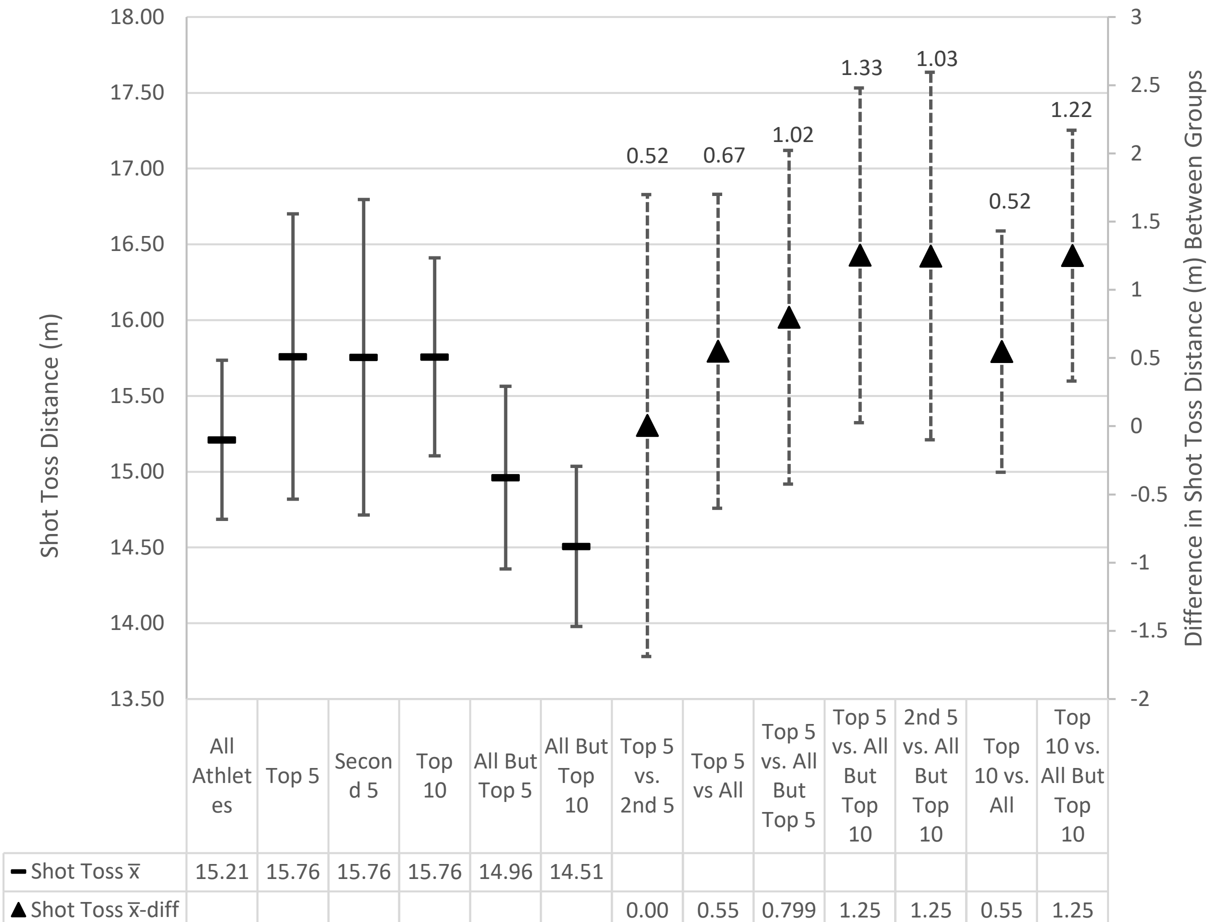
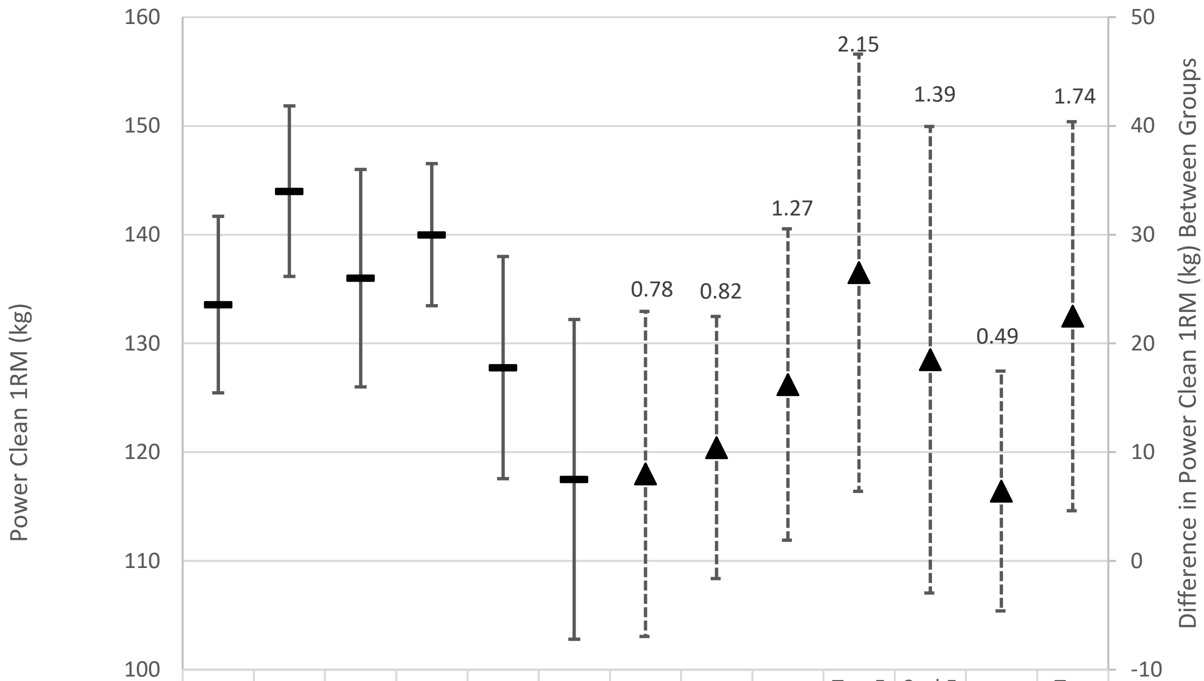


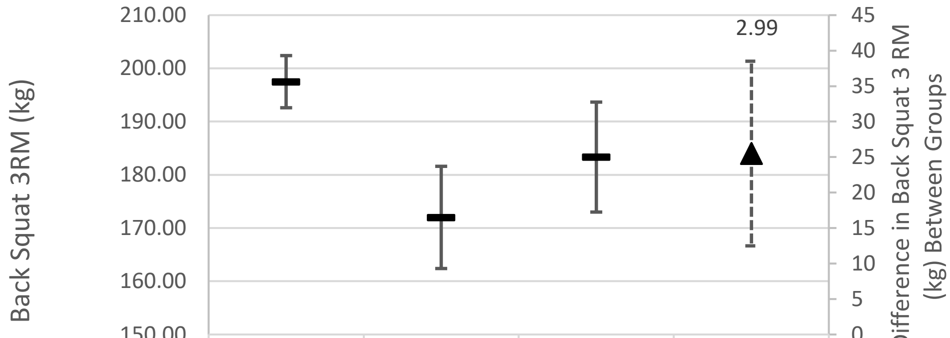
Figure 4.2. PPC 2014, UST distances for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.



	All Athletes	Top 5	Second 5	Top 10	All But Top 5	All But Top 10	Top 5 vs. 2nd 5	Top 5 vs All	Top 5 vs. All But Top 5	Top 5 vs. All But Top 10	2nd 5 vs. All But Top 10	Top 10 vs. All	Top 10 vs. All But Top 10
▬ Power Clean x̅	134	144	136	140	128	118							
▲ Power Clean x̅-diff							8.00	10.43	16.222	26.50	18.50	6.43	22.50

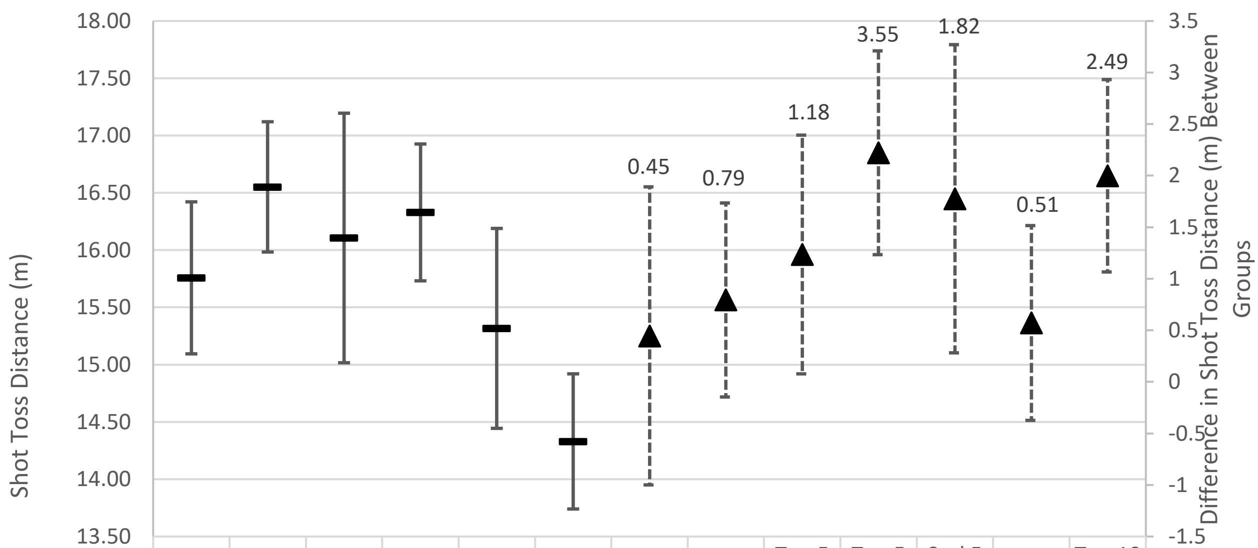
Figure 4.3. PPC 2014, 1RM PC loads for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.

Figures 4.4, 4.5, and 4.6 depict differences between group means for 1RM BS, UST, and body mass for the 2015 PPC. The two strongest effect sizes appear between the UST of TOP5 and NOTTOP10 ($\Delta\bar{x}$ = 2.22 m, *d* = 3.55), and between TOP5 and 2ND5 for 3RM BS ($\Delta\bar{x}$ = 25.5 kg, *d* = 2.99). Body mass was also relatively discriminatory between groups during the 2015 PPC with effect sizes of .94 < *d* < 2.01 for group mean comparisons with no overlapping subjects.



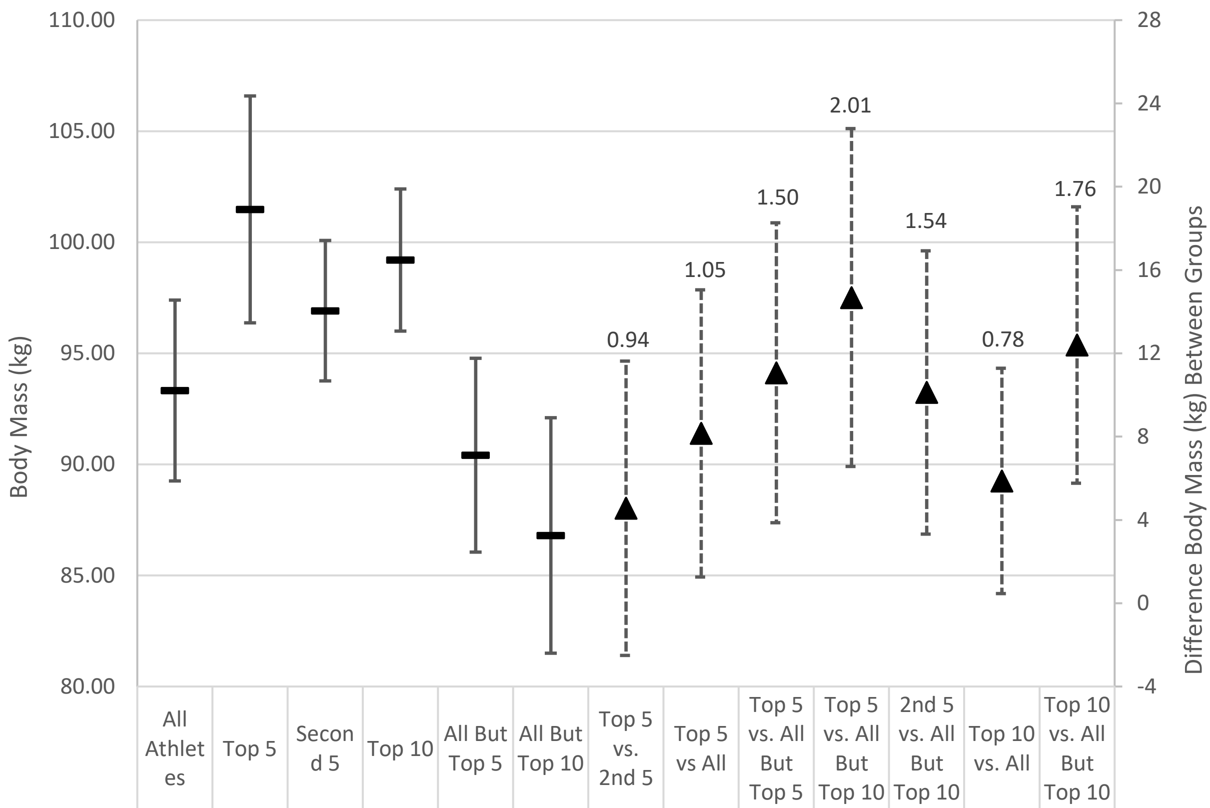
	Top 5	Second 5	Top 10	Top 5 vs. 2nd 5
▬ Back Squat 3RM x̄	197.50	172.00	183.33	
▲ Back Squat 3RM x̄-diff				25.50

Figure 4.4. PPC 2015, 3RM BS loads for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.



	All Athletes	Top 5	Second 5	Top 10	All But Top 5	All But Top 10	Top 5 vs. 2nd 5	Top 5 vs All	Top 5 vs. All But Top 5	Top 5 vs. All But Top 10	2nd 5 vs. All But Top 10	Top 10 vs. All	Top 10 vs. All But Top 10
▬ Shot Toss x̄	15.76	16.55	16.11	16.33	15.32	14.33							
▲ Shot Toss x̄-diff							0.45	0.79	1.235	2.22	1.78	0.57	2.00

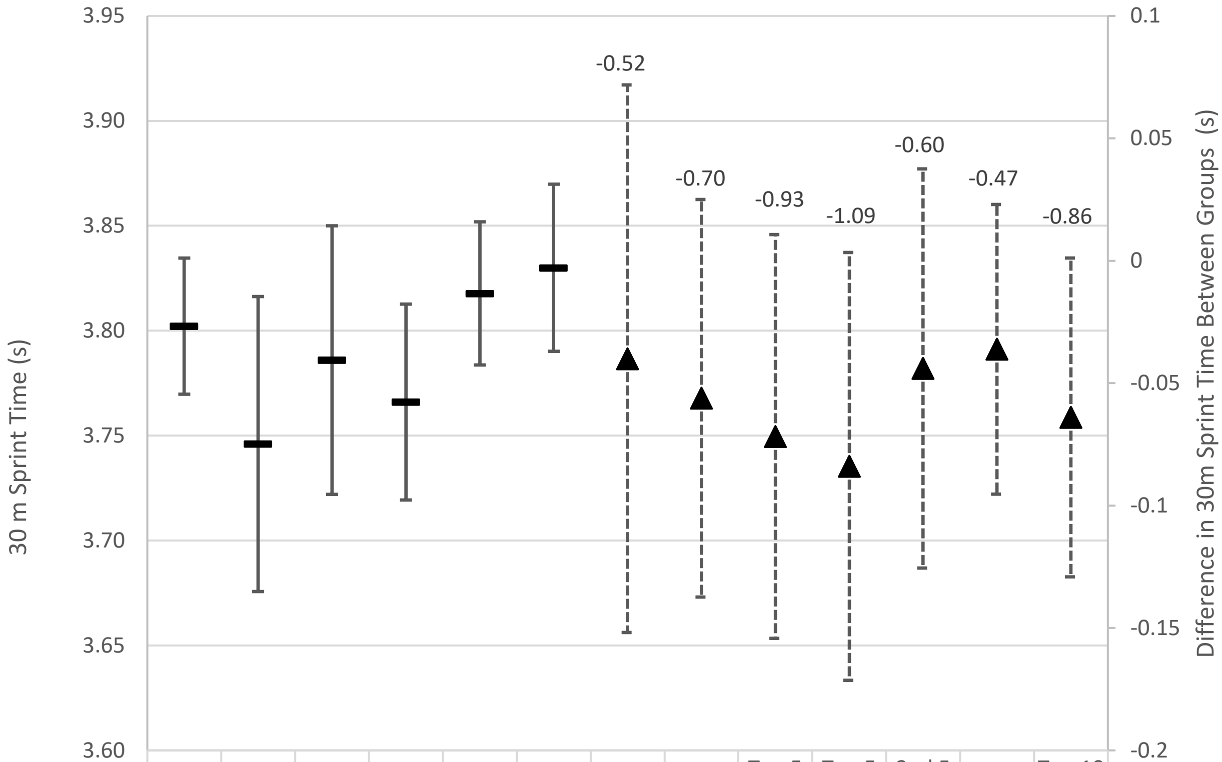
Figure 4.5. PPC 2015, UST distance for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.



	All Athletes	Top 5	Second 5	Top 10	All But Top 5	All But Top 10	Top 5 vs. 2nd 5	Top 5 vs All	Top 5 vs. All But Top 5	Top 5 vs. All But Top 10	2nd 5 vs. All But Top 10	Top 10 vs. All	Top 10 vs. All But Top 10
▬ BM x̄	93.33	101.48	96.92	99.20	90.41	86.80							
▲ BM x̄-diff							4.56	8.15	11.07	14.68	10.12	5.87	12.40

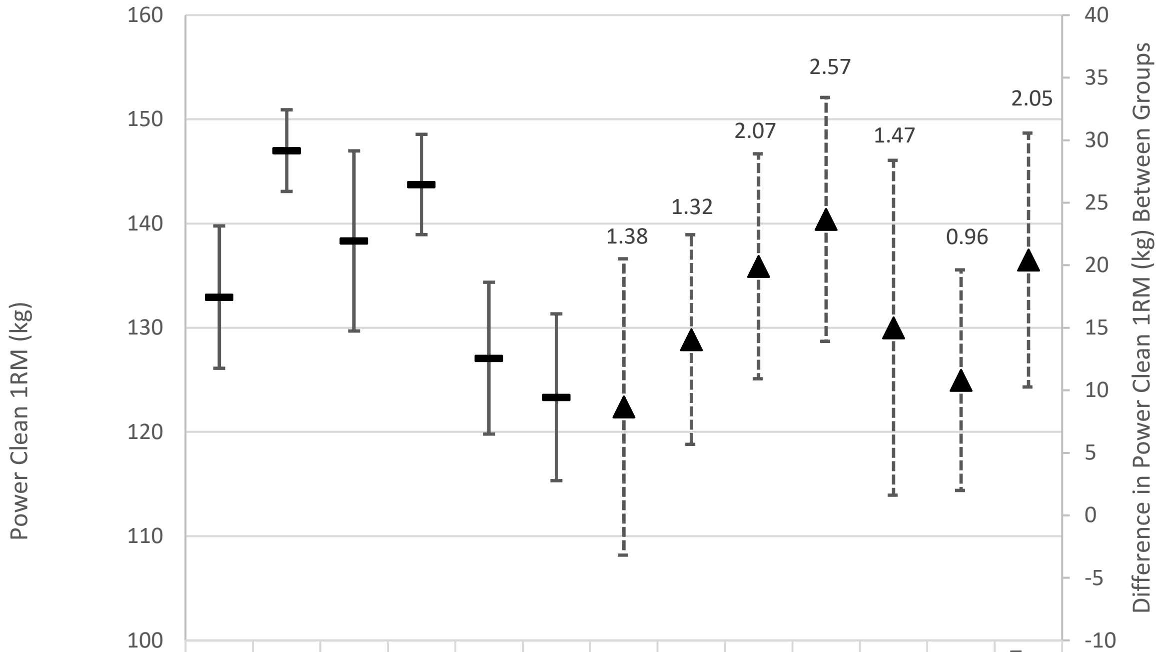
Figure 4.6. PPC 2015, Body mass for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.

Figures 4.7, 4.8, and 4.9 depict group means for the 30m, 1RM PC, and 3-ITEM for the 2014 NPC. The 30m times exhibited differences of .07 s and .06 s (*d* = -0.93, -0.86, respectively) when comparing TOP5 to NOTTOP5 and comparing TOP10 to NOTTOP10, respectively. Also in the 2014 NPC, the 1RM PC exhibited effect sizes of 1.32 < *d* < 2.57 for all comparisons between non-overlapping groups of athletes with differences in load ranging from 8.7 – 23.7 kg between various groups, with all faster-pushing groups outperforming slower-pushing groups.



	All Athlet es	Top 5	Secon d 5	Top 10	All But Top 5	All But Top 10	Top 5 vs. 2nd 5	Top 5 vs All	Top 5 vs. All But Top 5	Top 5 vs. All But Top 10	2nd 5 vs. All But Top 10	Top 10 vs. All	Top 10 vs. All But Top 10
▬ 30m x̄	3.80	3.75	3.79	3.77	3.82	3.83							
▲ 30m x̄-diff							-0.04	-0.06	-0.072	-0.08	-0.04	-0.04	-0.06

Figure 4.7. NPC 2014, 30m times for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.



	All Athletes	Top 5	Second 5	Top 10	All But Top 5	All But Top 10	Top 5 vs. 2nd 5	Top 5 vs All	Top 5 vs. All But Top 5	Top 5 vs. All But Top 10	2nd 5 vs. All But Top 10	Top 10 vs. All	Top 10 vs. All But Top 10
Power Clean x̄	133	147	138	144	127	123							
Power Clean x̄-diff							8.67	14.06	19.917	23.67	15.00	10.81	20.42

Figure 4.8. NPC 2014, 1RM PC loads for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.

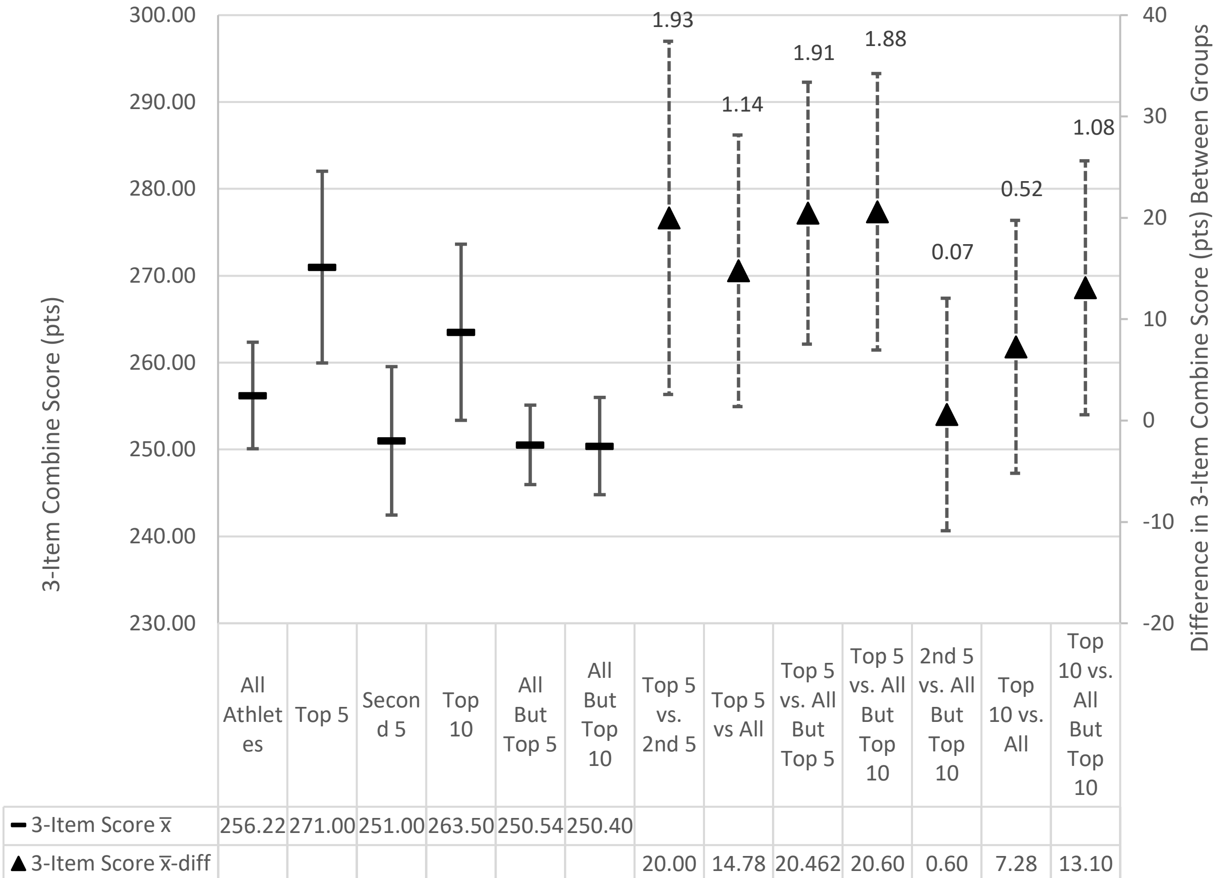


Figure 4.9. NPC 2014, 3-ITEM scores for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.

The only group pairings of the all the 91 independent t-tests carried out using data from the 2015 NPC that exhibit statistical significance in the difference of their means were five comparisons from the 3RM BS and 1RM PC (two and three, respectively). These are depicted visually in Figures 4.10 and 4.11. Specifically, the TOP10 and both subgroups within it (TOP5 and $2^{ND}5$) exhibited effect sizes ranging from $1.18 < d < 1.93$ in their comparisons with absolute differences between means of 6.9-13.8 kg between the faster pushing groups and all other compared slower-pushing non-overlapping groups.

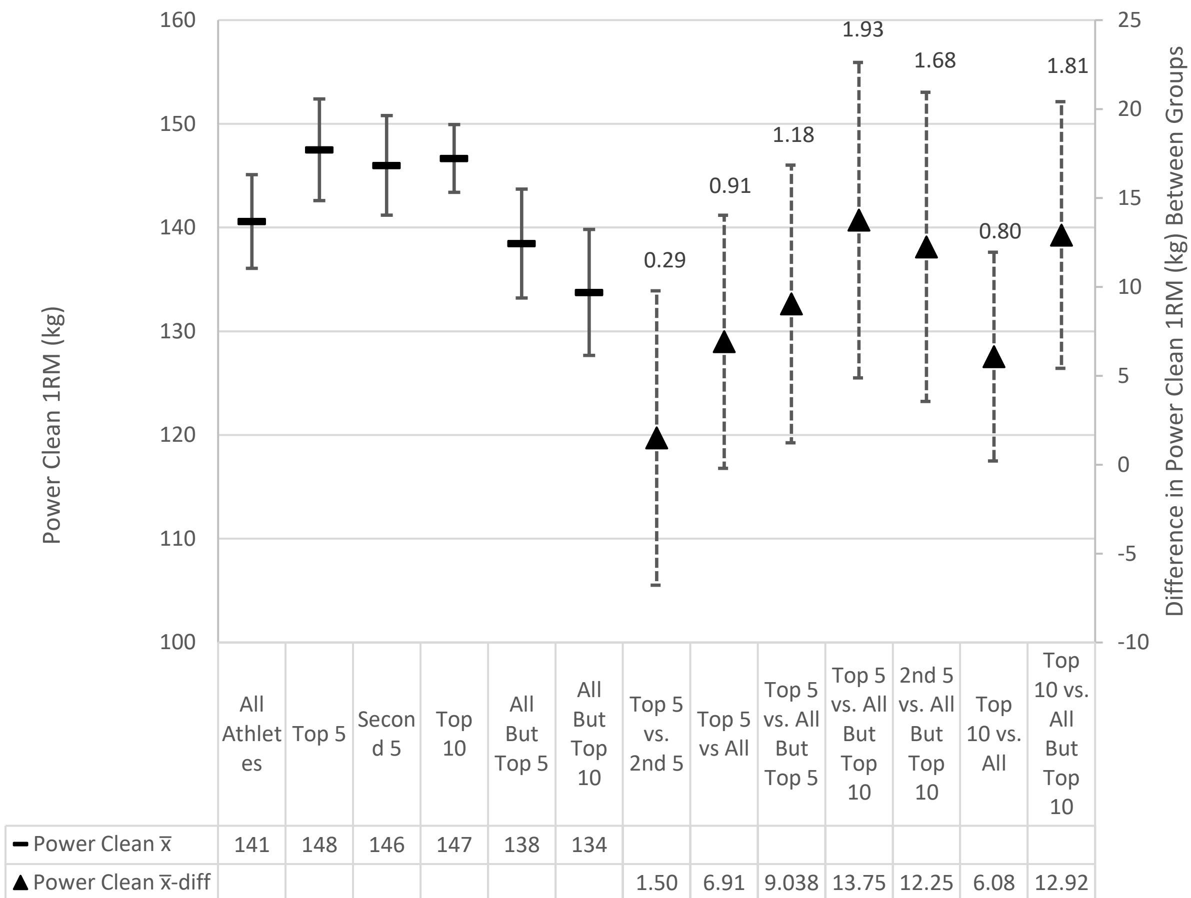
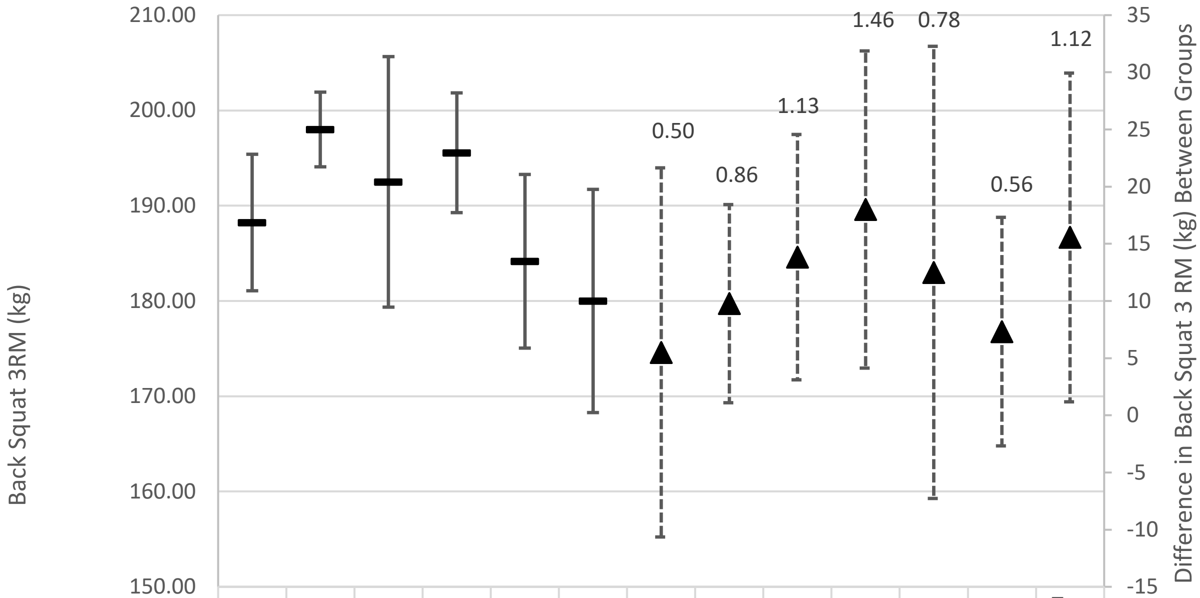


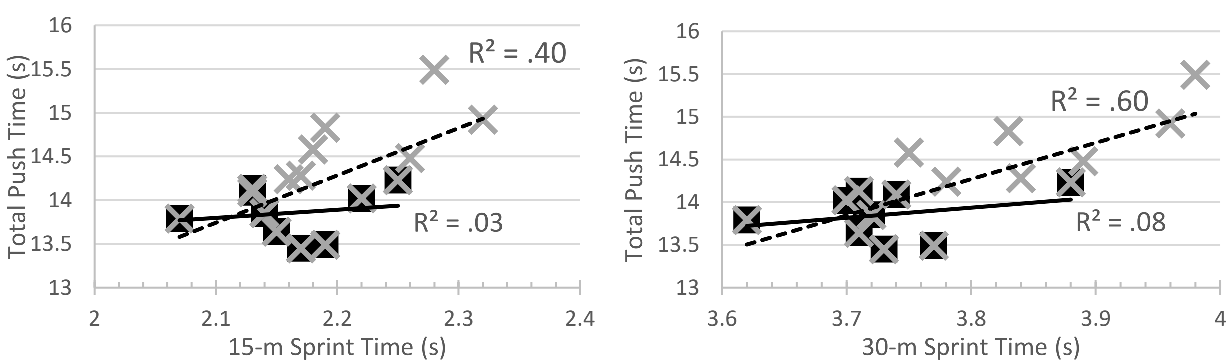
Figure 4.10. NPC 2015, 1RM PC loads for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.

The 3RM BS also produced similar findings in the 2015 NPC, with effect sizes ranging from $0.78 < d < 1.46$ with absolute mean differences of 12.5-18.0 kg between each higher-performing group of push athletes and NOTTOP10.

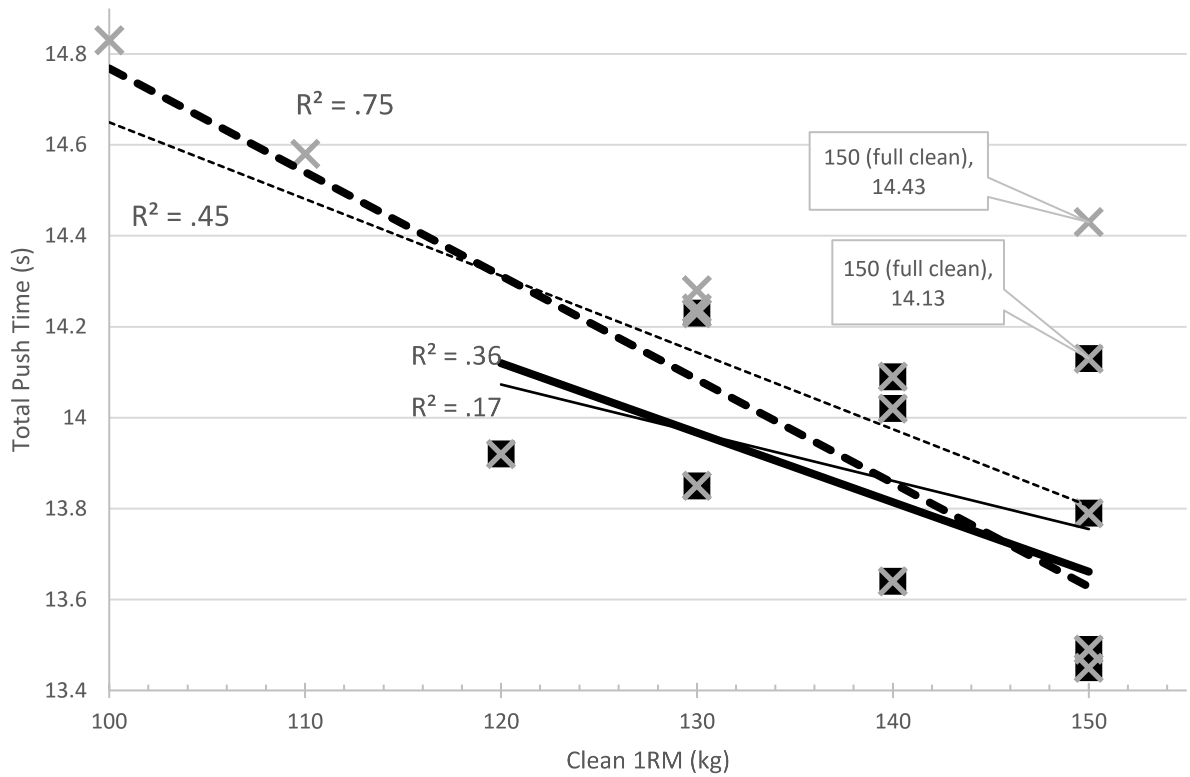


	All Athletes	Top 5	Second 5	Top 10	All But Top 5	All But Top 10	Top 5 vs. 2nd 5	Top 5 vs All	Top 5 vs. All But Top 5	Top 5 vs. All But Top 10	2nd 5 vs. All But Top 10	Top 10 vs. All	Top 10 vs. All But Top 10
▬ Back Squat 3RM x̄	188.24	198.00	192.50	195.56	184.17	180.00							
▲ Back Squat 3RM x̄-diff							5.50	9.76	13.833	18.00	12.50	7.32	15.56

Figure 4.11. NPC 2015, 3RM BS loads for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.



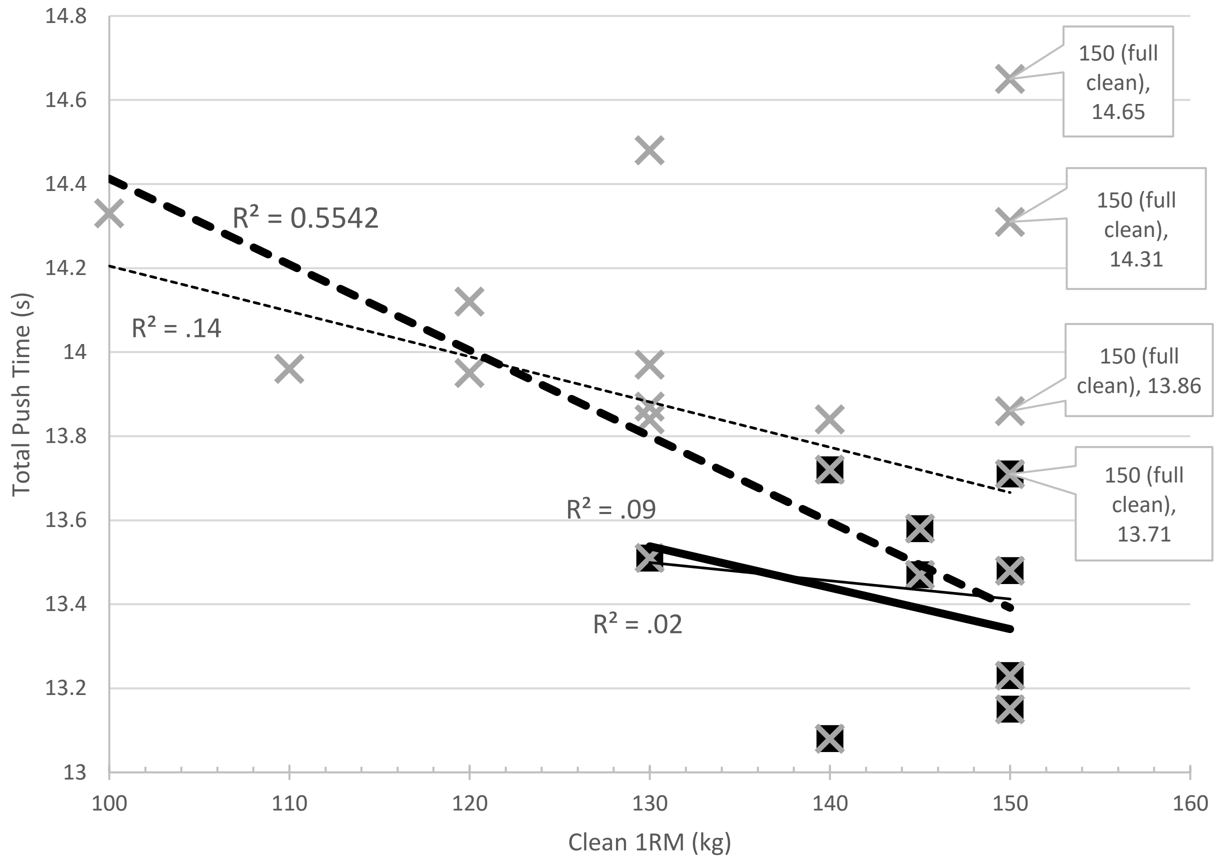
Figures 4.12 and 4.13. PPC 2014, 15m (left) and 30m (right) presented with linear regressions for TOP10 and ALL, and their respective R^2 values on the graph. Gray "X" and dashed trendline represents ALL athletes. Solid black box and solid black trendline represents TOP10 athletes.



Figures 4.14. PPC 2014, 1RM clean presented with linear regressions for TOP10 and ALL, and their respective R^2 values on the graph, alongside the analogous linear regressions using the data excluding athletes who used a "full" clean catch position during testing. Gray "X" and represents ALL athletes, with the thin dashed trendline representing all 1RM clean data and the bolded dashed trendline representing ALL athlete data excluding full cleans. Solid black box represents TOP10 athletes, with the solid thin trendline representing TOP10 1RM clean data, and the solid bolded trendline representing TOP10 1RM PC data only.

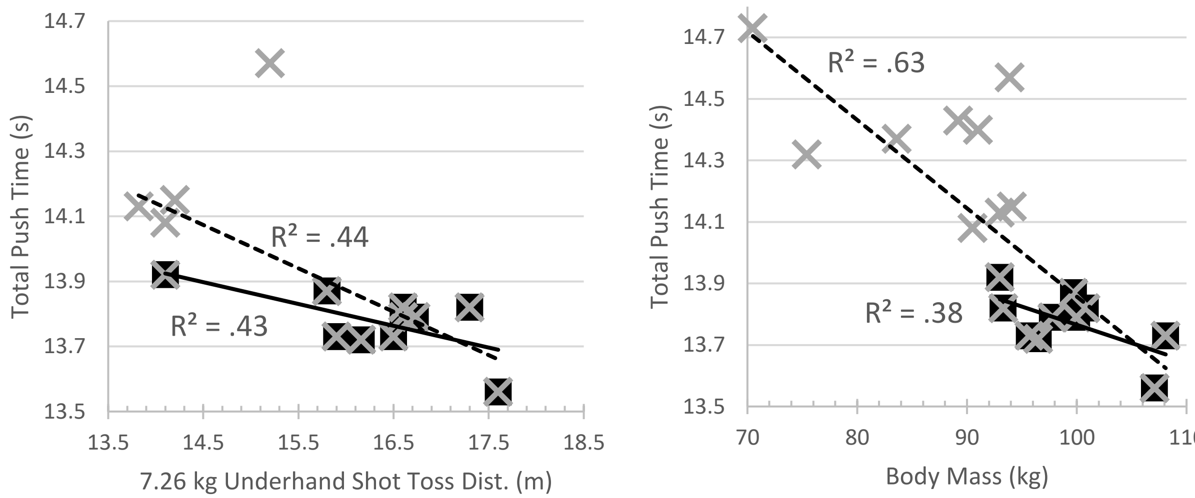
Figures 4.12 and 4.13 depict the regression analysis for the 15m and 30m as it relates to push time in the 2014 PPC. Significance values can be viewed previously for these regressions in Table 4.2 of this Results section. Statistical significance was only reached for these regressions when ALL athletes were analyzed. The 60m presented similar findings ($p < .01$) to the 15m and 30m and is no longer used by USABS in recruitment or monitoring so it was left out of the presented graphs.

The 1RM PC and 1RM clean data plotted individually against total push time for the 2014 PPC for comparison of regressions, with and without inclusion of athletes utilizing a "full" clean catch position during 1RM PC testing, are presented in Figure 4.14. The 2014 NPC data for the analysis is presented in Figure 4.15.

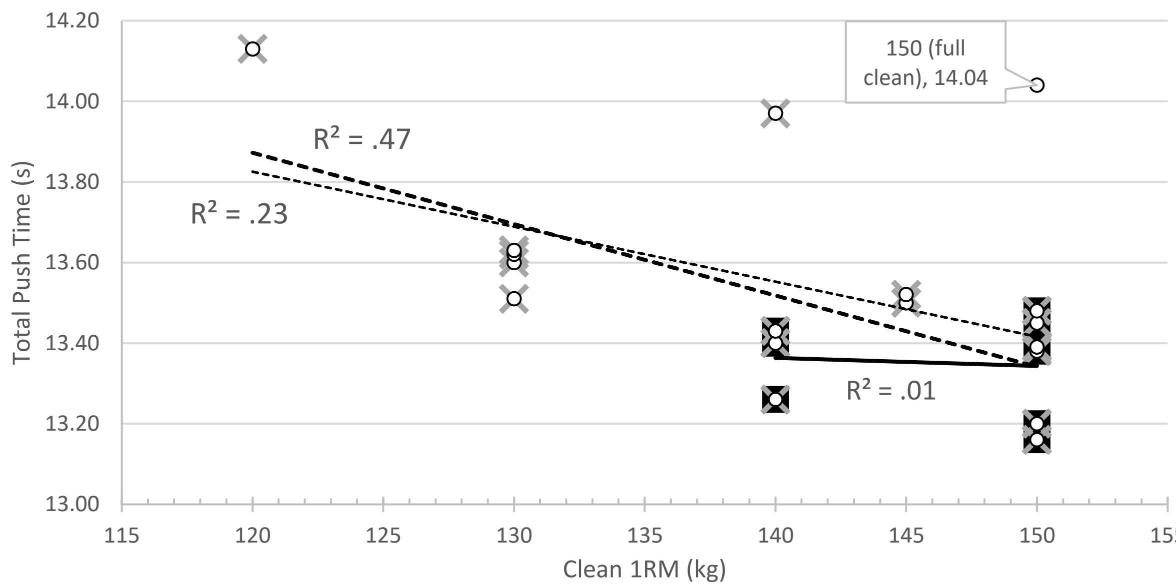


Figures 4.15. NPC 2014, 1RM clean presented with linear regressions for TOP10 and ALL, and their respective R^2 values on the graph, alongside the analogous linear regressions using the data excluding athletes who used a "full" clean catch position during testing. Gray "X" and represents ALL athletes, with the thin dashed trendline representing all 1RM clean data and the bolded dashed trendline representing ALL athlete data excluding full cleans. Solid black box represents TOP10 athletes, with the solid thin trendline representing TOP10 1RM clean data, and the solid bolded trendline representing TOP10 1RM PC data only.

The UST and body mass were the only two variables for which correlation statistical significance at a level of $p < .01$ was achieved when compared to total push time at the 2015 PPC. These data are presented in Figures 4.16 and 4.17.



Figures 4.16 and 4.17. PPC 2015, UST distance (left) and body mass (right) presented with linear regressions for TOP10 and ALL, and their respective R^2 values on the graph. Gray "X" and dashed trendline represents ALL athletes. Solid black box and solid black trendline represents TOP10 athletes.



Figures 4.18. NPC 2015, 1RM clean presented with linear regressions for TOP10 and ALL, and their respective R^2 values on the graph, alongside the analogous linear regression using the data excluding athletes who used a "full" clean catch position during testing. Open circle markers indicate ALL athletes regardless of clean technique employed. Gray "X" and represents ALL 1RM PC athletes, with a thin dashed trendline representing all 1RM clean data and the bolded dashed trendline representing ALL athlete data excluding one athlete who did a full clean. Solid black box represents TOP10 athletes, with the solid bolded trendline representing TOP10 1RM PC data, which was identical to the 1RM clean data because all athletes in TOP10 demonstrated true PC technique during testing.

In the 2015 NPC, the 1RM PC and UST were the two variables found to have statistical significance ($p < .01$) in prediction of total push time and are presented in Figures 4.18 and 4.19, respectively.

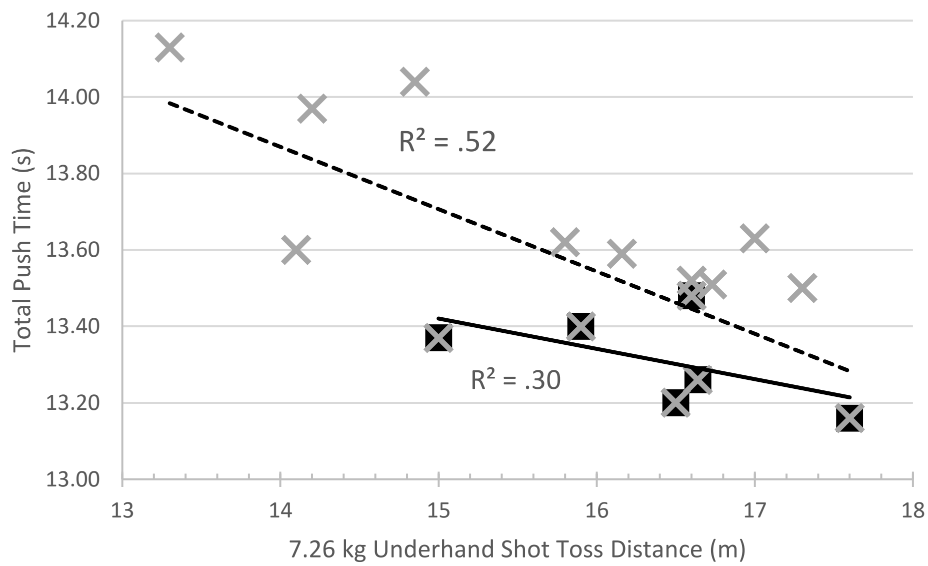
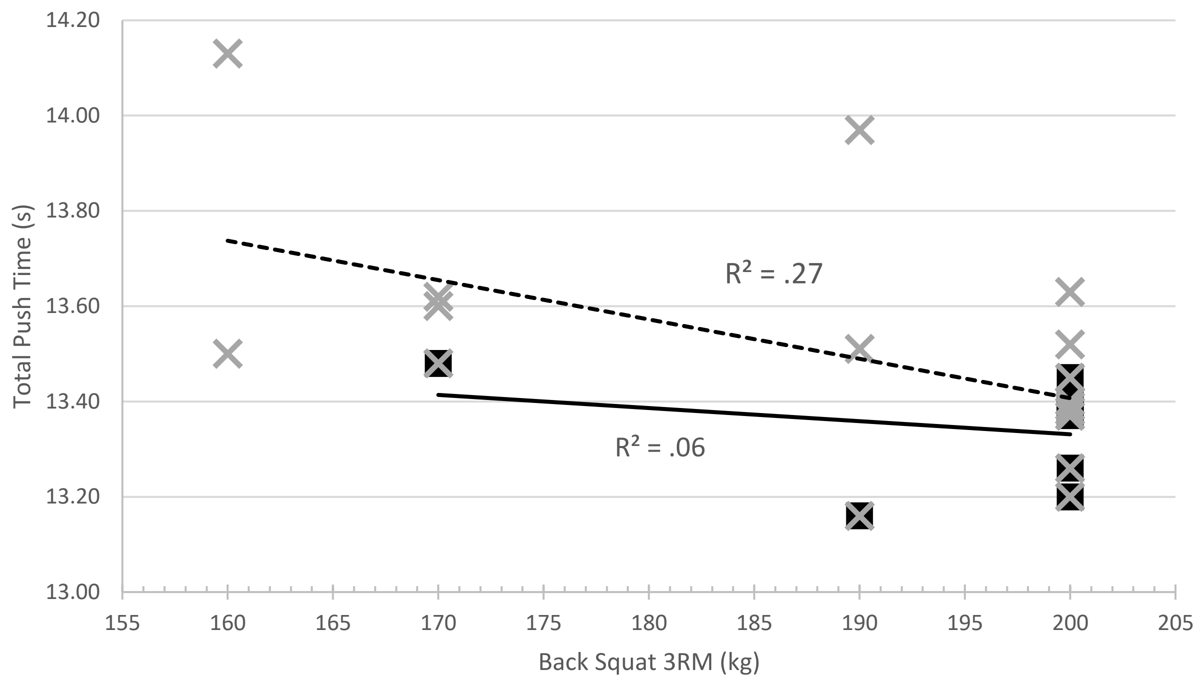


Figure 4.19. PPC 2015, UST distance (left) and body mass (right) presented with linear regressions for TOP10 and ALL, and their respective R^2 values on the graph. Gray "X" and dashed trendline represents ALL athletes. Solid black box and solid black trendline represents TOP10 athletes.

Because of the "capping effect" noted in the 1RM clean testing (Figures 4.14, 4.15, 4.18), caused presumably by the USABS scoring tables maxing out their scoring out of 100 points at 150 kg in the clean, a regression for the 3RM BS test was also carried out where data were available. Though the correlation between 3RM BS and total push time was not significant in the 2015 NPC, the data are presented in Figure 4.20. Seven of the nine available data points from TOP10 and nine of an available 17 data points from ALL athletes were at the combine scoring table maximum of 200kg. All other regressions and group mean comparison charts can be viewed in Appendices H-K.



Figures 4.20. NPC 2015, 3RM BS loads presented with linear regressions for TOP10 and ALL, and their respective R^2 values on the graph. Gray "X" and dashed trendline represents ALL athletes. Solid black box and solid black trendline represents TOP10 athletes.

DISCUSSION

The strongest and most frequently repeated findings of the present study revolved around the predictive validity and discriminative ability of power and strength tests in relation to total push time at both PPC and NPC in 2014 and 2015. Only when the level of athlete being examined was the lowest was speed a primary discriminator for push track success. This is in alignment with the findings of Osbeck and colleagues (1996) whose study reported on athletes of even lower level than the 2014 PPC group in the present study. Interestingly, their results demonstrated an even stronger relationship between sprint speed and push times than did the 2014 PPC, with a diminishing relationship of speed to push performance as the talent level of the push athlete deepened from 2014 PPC to the 2015 NPC. It is possible that there may be a threshold of either speed, or pushing ability, above which, added sprinting speed is no longer as beneficial as increasing strength or power output. This idea of a threshold is a topic that merits further investigation.

In the 2014 PPC the 1RM PC was the single most predictive variable of pushing performance among TOP10 athletes and was the only one to reach statistical significance. Interestingly, as the talent pool deepened and the loads completed in the 1RM PC increased, the relationship also decreased among TOP10 athletes, but not among ALL athletes. While the 1RM PC discriminated between TOP5 and 2ND5 athletes at the 2014 PPC, it became less different between the top-level athletes during the three other push championships. Given visual inspection of Figures 4.14, 4.15, 4.18, it should be noted that increasingly more athletes attained the USABS scoring maximum (100 pts) (Skeleton, 2017f) for successfully completing a 1RM PC of 150 kg, and no higher weights were attempted because of no perceived reward by the athletes. The 1RM PC may be more useful as a predictor or discriminator of push performance if athletes are encouraged to find a true 1RM, as opposed to seeking to score a maximum of 100 points on the USABS combine scoring tables (Skeleton, 2017f). Further, the validity of the 1RM PC for its purpose as a predictor of push performance is greatly diminished when athletes can use a full clean technique because of the lower bar velocity required upon execution of the ‘second pull.’

The UST became increasingly predictive and discriminative of bobsled push performance moving chronologically from the 2014 PPC to the 2015 PPC, in alignment with what might have been expected if the capping effect of the 1RM PC wasn’t as prevalent. UST became most discriminative of bobsled push performance in the 2015 PPC where it single-handedly predicted over 40% of the variability in pushing performance of both TOP10 and ALL athletes, independently, and expressed effect sizes of 1.18 to 3.55 when comparing TOP5 athletes to all other groups. Because the threshold for the UST is less likely to be achieved (zero athletes scored 100 points for an 18-m throw), compared to the 1RM PC (over half of all athletes at 2015 NPC achieved a maximum score of 100 points at 150 kg lifted), the predictive and discriminative ability of the distances thrown tends to be better among higher level push athletes.

There was limited data available for 3RM BS in relation to bobsled pushing performance but it was the single most consistent dependent variable for its discriminative ability between groups of higher-level push athletes, even with the capping effect (USABS defines 100 points as 200 kg) (Skeleton, 2017f) that is clearly visible in Figure 4.19. Specifically, there was a difference of over 25 kg in 3RM BS between TOP5 and 2ND5 athletes at the 2015 PPC. However, among TOP10 athletes this difference vanished at the 2015 NPC, likely because seven out of nine available data points for 3RM BS were at 200 kg and no athletes sought to exceed the artificial barrier placed by the USABS points system (Skeleton, 2017f). It seems plausible that the meaningfulness of the 3RM BS as an indicator of pushing performance would be improved dramatically if there were no maximum limit to its performance based on an arbitrary scoring table.

Previously, numerous authors have identified a direct positive relationship between strength and sprinting speed (Baker & Nance, 1999; Comfort et al., 2012; Comfort et al., 2014; McBride et al., 2009). Similarly, many researchers have identified strong relationships between power output and sprint speed over various distances where the tests of power output have no maximum limit of performance (Baker & Nance, 1999; Bellon, 2016; Comfort et al., 2014; Dal Pupo, Arins, Guglielmo, da Silva, et al., 2010; Sleivert & Taingahue, 2004). It has also been demonstrated repeatedly that stronger athletes experience smaller decreases in power output and velocity of movement under incrementally increased loads (Haun et al., 2017; Kraska, Ramsey, Gregory, et al., 2009). The most pronounced decreases in speed and power found by Haun and colleagues (2017) were present when the external load approached body weight of the athletes. Given that the external weight of the bobsled is at least effectively 55 kg per athlete in 4-man bobsled or at least 85 kg per athlete in 2-man bobsled, (Federation, 2016e) it seems likely that if a threshold for diminishing returns of strength and power exists, it is very high, since no such threshold has been demonstrated in the literature to date.

As with any athlete testing for monitoring or talent identification, it is critical that the testing be standardized. In the case of dynamic constant external resistance (DCER) testing like the 3RM BS, the depth of the squat must be better standardized to prevent faulty conclusions from being drawn by coaches, athletes, and national team selection committees.

Evidence for a threshold above which further increases in speed are minimally beneficial in bobsled pushing is multi-fold. First, ground contact times during sled acceleration may need to be longer than sprint acceleration ground contact times for successful pushing (Coh & Tomazin, 2006; Park et al., 2015; Smith et al., 2007). Longer ground contact times have been demonstrated during a 15 m sled push in faster groups of push athletes as compared to slower national level push athletes (Park et al., 2015). These athletes exhibited lower knee and hip flexion ranges of motion but higher ankle joint range of motion, creating longer ground contacts through lower foot passage over the ground's surface (Park et al., 2015). This concept is often termed "low heel recovery" within track and field and bobsled. These findings are congruent with the impulse-momentum relationship wherein increased time of force application at equivalent, or even slightly reduced peak or average forces, may result in greater impulse and thus greater change in momentum (acceleration) of a sled-athlete system.

Further, Hoffman and colleagues reported that athletes who naturally express longer ground contact times during unresisted sprints tend to push heavy sleds faster than those with shorter ground contact times during unresisted sprints.(Hoffman Jr., 2014) The same group of researchers also reported that faster athletes did indeed push sleds faster in agreement with the findings of the present study and others (Hoffman Jr., 2014; Osbeck et al., 1996). These findings are a bit paradoxical given that it is reasonably well established that ground contact times and rates of force development are limiting factors in sprint speed (Kuitunen et al., 2002; Mero et al., 1992; Weyand et al., 2010; Weyand et al., 2000). It seems plausible then to conclude as experts in the field have already, (Dabnichki, 2016; DeWeese et al., 2014; Sato & Suzuki, 1991) that bigger, relatively fast, strong and highly powerful athletes with naturally longer ground contact times as compared with slightly faster, lighter, or weaker athletes could make better bobsled push athletes.

It is possible, too, that the reason for the diminished relationship between speed and pushing ability at the highest level of the sport, as has been reported on by other experts in the sport of bobsled, (Dabnichki, 2016; Sato & Suzuki, 1991) is that athletes who express very fast unresisted sprint times not only tend to have more rigid ankles which may shorten ground contact time, (Kuitunen et al., 2002; Mero et al., 1992) but they may also be smaller in stature and thus express lower absolute power and strength (Dabnichki, 2016; DeWeese et al., 2014; Kirkendall & Street, 1986). Indeed many nations seek to recruit the fastest sprinters available for bobsled pushing but are repeatedly out-pushed internationally by larger more powerful crews of brakemen.

From a physical standpoint, the necessity of high sprinting speed for pushing on ice may also be negated slightly by the ability to use the normal forces due to gravity to accelerate the sled on the push ramp which slopes down sharply after 15-20 m of slight decline (Federation, 2016e). Stronger, more powerful push athletes may be able to accelerate the sled to their respective maximum velocities several meters earlier than faster, but weaker bobsled push athletes because stronger athletes are affected less than weaker athletes when faced with equivalent external load (Haun et al., 2017; Kraska, Ramsey, Gregory, et al., 2009). Thus, the more powerful athlete may be able to utilize an earlier loading strategy and still achieve greater velocity at the 65-m timing eye than the faster athlete who, via conventional wisdom, should attain a higher velocity.

A final constraint placed on the bobsled athlete and their crew, although not investigated presently, is that any weight underneath the sled maximum that the crew weighs in at for a race, could be costly in energetic losses. Thus, weights are generally added to the sled up to very near the maximum sled-plus-crew weight, further adding disadvantage to smaller brakemen who in race scenarios must push heavier sleds than their larger counterparts. This was not the case in the push championships analyzed but could further the already-strong relationships between absolute strength and power and pushing performance as athletes move from pre-season push championships to international bobsled racing.

PRACTICAL APPLICATION

It is proposed that bobsled athletes, coaches, and national team selection committees consider more strongly the necessity of strength and power to overcome external resistance at high velocities. The 1RM PC, and 3RM BS, if standardized are meaningful and predictive tests in relation to bobsled pushing performance on the Lake Placid push track where the 2014 and 2015 PPC and NPC typically take place and given the mechanical similarity of that push track to competitive bobsled pushing, it is likely that the relationship is high between push track performance and on-ice performance.

The validity of the tests used for monitoring is of especially high importance because of the tendency of athletes and coaches to train to the test if it is known that the selection committee or coaches place any weight in the monitoring tests results for pre-season, in-season, or championship team selection. Any lack of validity between the test and the actual performance could lead to the inclusion of training methodology not useful for actual bobsled pushing performance to ensure an athlete's position within the team is not lost, thereby reducing the focus of training on the pushing performance.

Thus, it is suggested that more specific strength- or power-tests to bobsled, using more sport-specific joint angles are implemented in the future. Considering limited equipment that is typically transported with bobsled teams, hanging weightlifting derivatives, or weighted jump squats on an electronic jump mat that reports jump height may be reasonable alternatives to the current protocol used in monitoring which usually consist of speed-testing only, in-season.

Further research is needed on the specific interplay between sprint speed, strength, power, and ground contact time utilized in both unresisted and resisted sprinting. It is possible a measure of ankle dorsiflexion range of motion could be predictive of bobsled pushing performance alongside sprint speed and a measure of strength or power output. These taken together could provide a more useful talent identification testing battery, if validated.

While speed is critical for bobsled pushing performance at the national team level, increasing speed or seeking ever-faster athletes may have more rapidly diminishing returns than increasing strength or power output or recruiting relatively fast, highly powerful and strong athletes. Acceleration mechanics training to enhance the duration of ground contact during the first 15 m of sled pushing is warranted, so that the trained strength and power output can be expressed through increased impulse applied to the bobsled.

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CHAPTER 5

CONCLUSION

Summary of Findings: Interrelationship of Start, Split, and Finish Times and Velocities

The first investigation found relatively high reliability within start time measurements between heats (ICC = .94, average), but not start velocity measurement (ICC = .80, average). Weather, specifically snowfall appeared to be a confounding variable for both. However, the standardization of the measurement of start time as a 50-m split time at the beginning of every race, taken from 15-65 m on all tracks allowed for reasonable reliability to be attained. This was not the case for velocity measurement. Tracks where velocity measurement results in velocities higher than 55 km/hr likely are using some measurement that is less than instantaneous, resulting in the velocity being affected by factors outside of the push and loading paradigm of the crew. Thus, it is recommended that velocity measurements be standardized for all tracks by the IBSF, and that until that happens, coaches interpret velocity data with caution as a means of judging push performance.

Start times are strongly predictive of velocity, though where velocity is measured down-track or less reliably that relationship diminishes. Start time and velocity both predict finish time relatively equivalently (39 and 43%, $p < .05$) as an average of all tracks in the world with no meaningful difference between 2- and 4- man bobsled. It is suggested that the velocity prediction ability could be further enhanced with increased reliability of measurement, but that it could also be reduced by moving the velocity measurement closer to the 65-m timing eyes at the end of the push ramp.

The relationship between the start variables is probably inflated because of a “stacking the deck” effect caused by each nations interest to have at least one sled in the medal hunt.

Pairing the best brakemen with the best-driving pilot and the best materials is probably the explanation for the maintenance of the mathematical relationship between the start variables and the times taken to cover various subsections of the track nearly three quarters of a mile away.

Summary of Findings: Field Testing Correlates for Bobsled-Pushing

It is apparent that absolute measures of strength and power offer the greatest validity for predicting bobsled pushing performance or for discriminating between various levels of push athlete at PPC and NPC. Unresisted sprint speed is also a critical component of bobsled pushing performance but seeking to recruit or train speed at the sacrifice of high-level strength and power appears to be a faulty strategy.

Any tests that are used henceforth in identifying talent for bobsled pushing or for monitoring bobsled push athlete development should be more well standardized that the system currently in place. If 3RM BS will continue as the selected measure of strength for USABS it is necessary to improve upon standardization of squat depth. Similarly, if 1RM PC will be a permanent fixture of the USABS 8-item combine, it is necessary to mandate it be complete as a true “power” clean, and coaches and practitioners responsible for overseeing the testing must enforce the disqualification athletes who use the “full” clean technique. The predictive validity of the 1RM PC for bobsled pushing performance at the PPC and NPC level is doubled when only power cleans are included.

Performance ceiling effects in testing due to athletes’ ability to routinely attain the test performance required for a maximum score of 100 points on the USABS combine scoring tables must be avoided as well. As number of athletes attaining the maximum score increases the ability of the performance metric to discriminate between groups or predict pushing performance decreases dramatically. This is currently seen in both the 1RM PC and the 3RM BS, with more than half the athletes at the 2015 NPC attaining a maximum of 100 points on both tests (150 kg 1RM PC, 200 kg 3RM BS, respectively).

There exists a wide variability in pushing performance when looking at any one variable among TOP10 athletes within USABS. This is indicative of either missing pieces in the prediction ability of the athlete monitoring, or widely variable push technique, or both. Given the findings of Smith and colleagues, as well as the findings of Sato and colleagues,(Sato & Suzuki, 1991; S. L. Smith et al., 2007) it is suggested that athletes, practitioners, and bobsled coaches work fervently to improve the sled pushing technique of the national team athletes so that maximum impulse can be applied for each given athletes biomotor and anthropometric qualities. It is the present author's opinion that not enough attention is paid to training for increased duration of ground contact time during the first 15 m of bobsled pushing in either USABS or internationally. It is only through sound bobsled pushing mechanics that the biomotor abilities of the athletes can be fully expressed in their pushing performance.

Future Research Direction

Beyond biomotor abilities like speed and strength, there are still significant predictive pieces missing from the athlete monitoring and talent identification battery that USABS currently uses annually. It is suggested that some measure of ground contact time during sprint running, or sled pushing, or some predictor thereof, like ankle dorsiflexion range of motion or limb lengths be investigated further. It is also suggested that either weighted jumps for height, or partial weightlifting movements be incorporated into the testing battery for monitoring athletes because of their probable higher validity for predicting bobsled pushing performance than the current tests. There currently exists a protocol using the isometric mid-thigh pull that allows for great standardization, simplicity, and truly maximal testing without undue fatigue that has correlated strongly to power output and sporting performance (Kraska, Ramsey, Gregory, et al., 2009; Stone et al., 2004; Stone, O'bryant, et al., 2003; Stone, Sanborn, et al., 2003; Stone et al., 2007) It is recommended that this protocol is used in the future for monitoring and talent identification because of these advantages and the ability to tease out other potentially meaningful indicators of power performance like RFD.

Much more research is needed on team composition for 4-man bobsled as well. The present study only examines solo pushing and only on a rubberized push track. Ice pushes with teams in a facility like Calgary’s ice-house would be highly useful for informing decisions about team composition based on both push time and velocity measurements available at 5 m intervals in the current ice house.

As increased standardization of velocity measurement becomes the norm, a replication of the present study would be useful. Further, adding several more years’ data to the current data compilation would enhance understanding of track-specific push to split time relationships. A more involved means, but much more useful method of studying each track would be to obtain more frequent time and velocity measurements along each track as has been done in Calgary and Lillehammer.

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Appendix A

International Championship Medal Results since 1947

Table 2.7. Olympic 4-Man Bobsled Medal Results in the post-WWII era.

Olympic 4-Man Bobsled Results (post-WWII)																																						
		GER			SUI			USA			RUS			LAT			CAN			GBR			FRA			AUT			ITA			BEL			ROU		
Year	**Host City**	**G**	**S**	**B**	**G**	**S**	**B**	**G**	**S**	**B**	**G**	**S**	**B**	**G**	**S**	**B**	**G**	**S**	**B**	**G**	**S**	**B**	**G**	**S**	**B**	**G**	**S**	**B**	**G**	**S**	**B**	**G**	**S**	**B**	**G**	**S**	**B**
2014	Sochi									1	1				1																						
2010	Vancouver		1					1											1																		
2006	Turin	1					1					1																									
2002	Salt Lake City	1							1	1																											
1998	Nagano	1				1																1			1												
1994	Lillehammer	1		1		1																															
1992	Albertville		1			1																				1											
1988	Calgary		1		1								1																								
1984	Sarajevo	1	1				1																														
1980	Lake Placid	1		1		1																															
1976	Innsbruck	1		1		1																															
1972	Sapporo			1		1																								1							
1968	Grenoble					1																					1		1								1
1964	Innsbruck																1										1				1						
1956	Cortina D'Ampezzo				1					1																				1							
1952	Oslo	1					1		1																												
1948	St. Moritz							1		1																							1				
Totals (G, S, B)		8	4	4	2	7	3	2	2	4	1	1	1	0	1	0	1	0	1	0	0	1	0	0	1	1	2	0	1	2	1	0	1	0	0	0	1
Total Medals		**16**			**12**			**8**			**3**			**1**			**2**			**1**			**1**			**3**			**4**			**1**			**1**		
Weighted Point Totals		116			67			46			19			5			14			4			4			20			24			5			4		
		GER			**SUI**			**USA**			**RUS**			**LAT**			**CAN**			**GBR**			**FRA**			**AUT**			**ITA**			**BEL**			**ROU**		

Data compiled from: https://www.olympic.org/olympic-results. (Committee, 2016)

Table 2.8. Olympic 2-Man Bobsled Medal Results in the post-WWII era.

Olympic 2-Man Bobsled Results (post-WWII)																																					
		GER			SUI			USA			RUS			LAT			CAN			GBR			FRA			AUT			ITA			BEL			ROU		
Year	**Host City**	**G**	**S**	**B**	**G**	**S**	**B**	**G**	**S**	**B**	**G**	**S**	**B**	**G**	**S**	**B**	**G**	**S**	**B**	**G**	**S**	**B**	**G**	**S**	**B**	**G**	**S**	**B**	**G**	**S**	**B**	**G**	**S**	**B**	**G**	**S**	**B**
2014	Sochi					1				1	1																										
2010	Vancouver	1	1										1																								
2006	Turin	1				1											1																				
2002	Salt Lake City	1				1	1																														
1998	Nagano			1													1												1								
1994	Lillehammer				1	1																									1						
1992	Albertville		1	1	1																																
1988	Calgary		1	1							1																										
1984	Sarajevo	1	1										1																								
1980	Lake Placid		1	1		1																															
1976	Innsbruck	1	1				1																														
1972	Sapporo	1	1				1																														
1968	Grenoble		1																										1								1
1964	Innsbruck																			1										1	1						
1956	Cortina D'Ampezzo					1																							1	1							
1952	Oslo	1					1		1																												
1948	St. Moritz				1	1				1																											
Totals (G, S, B)		7	8	4	3	7	4	0	1	2	2	0	2	0	0	0	2	0	0	1	0	0	0	0	0	0	0	0	3	2	2	0	0	0	0	0	1
Total Medals		**19**			**14**			**3**			**4**			**0**			**2**			**1**			**0**			**0**			**7**			**0**			**1**		
Weighted Point Totals		126			81			13			28			0			20			10			0			0			48			0			4		
		GER			**SUI**			**USA**			**RUS**			**LAT**			**CAN**			**GBR**			**FRA**			**AUT**			**ITA**			**BEL**			**ROU**		

Data compiled from: https://www.olympic.org/olympic-results. (Committee, 2016)

Table 2.9. Combined Olympic Bobsled Medal Results in the post-WWII era.

Olympic Combined Bobsled Results (post-WWII)																																					
		GER			SUI			USA			RUS			LAT			CAN			GBR			FRA			AUT			ITA			BEL			ROU		
Year	**Host City**	**G**	**S**	**B**	**G**	**S**	**B**	**G**	**S**	**B**	**G**	**S**	**B**	**G**	**S**	**B**	**G**	**S**	**B**	**G**	**S**	**B**	**G**	**S**	**B**	**G**	**S**	**B**	**G**	**S**	**B**	**G**	**S**	**B**	**G**	**S**	**B**
2014	Sochi					1				2	2				1																						
2010	Vancouver	1	2					1					1						1																		
2006	Turin	2				1	1					1					1																				
2002	Salt Lake City	2				1	1		1	1																											
1998	Nagano	1		1		1											1					1			1				1								
1994	Lillehammer	1		1	1	2																									1						
1992	Albertville		2	1	1	1																				1											
1988	Calgary		2	1	1						1		1																								
1984	Sarajevo	2	2				1						1																								
1980	Lake Placid	1	1	2		2																															
1976	Innsbruck	2	1	1		1	1																														
1972	Sapporo	1	1	1		1	1																							1							
1968	Grenoble		1			1																					1		2								2
1964	Innsbruck																1			1							1			1	2						
1956	Cortina D'Ampezzo				1	1				1																			1	2							
1952	Oslo	2					2		2																												
1948	St. Moritz				1	1		1		2																							1				
Totals (G, S, B)		15	12	8	5	14	7	2	3	6	3	1	3	0	1	0	3	0	1	1	0	1	0	0	1	1	2	0	4	4	3	0	1	0	0	0	2
Total Medals		**35**			**26**			**11**			**7**			**1**			**4**			**2**			**1**			**3**			**11**			**1**			**2**		
Weighted Point Totals		242			148			59			47			5			34			14			4			20			72			5			8		
		GER			**SUI**			**USA**			**RUS**			**LAT**			**CAN**			**GBR**			**FRA**			**AUT**			**ITA**			**BEL**			**ROU**		

Data compiled from: https://www.olympic.org/olympic-results. (Committee, 2016)

Table 2.10. World Championship 4-Man Bobsled Medal Results in the post-WWII era.

World Championship 4-Man Bobsled Results (post-WWII)																																											
		GER			SUI			USA			RUS			LAT			CAN			GBR			FRA			AUT			ITA			BEL			ROU			SWE			ESP		
Year	Host City	G	S	B	G	S	B	G	S	B	G	S	B	G	S	B	G	S	B	G	S	B	G	S	B	G	S	B	G	S	B	G	S	B	G	S	B	G	S	B	G	S	B
1947	St. Moritz				1																				1								1										
1949	Lake Placid						1	1	1																																		
1950	Cortina D'Ampezzo					1	1	1																																			
1951	Alpe d'Huez	1					1		1																																		
1953	Garmisch-Partenkirchen		1	1				1																																1			
1954	Cortina D'Ampezzo		1	1		1																																					
1955	St. Moritz			1	1	1																																					
1957	St. Moritz					1				1																				1													
1958	Cortina D'Ampezzo	1	1																												1												
1959	St. Moritz			1				1																						1													
1960	Cortina D'Ampezzo		1				1																								1												
1961	Lake Placid								1																				1											1			
1962	Garmisch-Partenkirchen	1																										1		1													
1963	Igls																											1	1	1													
1965	St. Moritz									1							1													1													
1966	Cortina D'Ampezzo*	1																																									
1967	Alpe d'Huez**																																										
1969	Lake Placid	1								1																				1													
1970	St. Moritz		1				1																						1														
1971	Cervinia			1	1																									1													
1973	Lake Placid			1	1																						1																
1974	St. Moritz	1				1																						1															
1975	Cervinia		1		1																							1															
1977	St. Moritz	1		1		1																																					
1978	Lake Placid	1		1		1																																					
1979	Konigssee	1	1				1																																				
1981	Cortina D'Ampezzo	1				1	1																																				
1982	St. Moritz		1		1		1																																				
1983	Lake Placid		1	1	1																																						
1985	Cervinia	1	1				1																																				
1986	Konigssee				1		1																				1																
1987	St. Moritz		1		1		1																																				
1989	Cortina D'Ampezzo			1	1	1																																					
1990	St. Moritz		1		1																							1															
1991	Altenberg	1		1		1																																					
1993	Igls				1					1																	1																
1995	Winterberg	1		1																							1																
1996	Calgary	1		1		1																																					
1997	St. Moritz	1	1					1																																			
1999	Cortina D'Ampezzo					1													1				1																				
2000	Altenberg	1	1			1																																					
2001	St. Moritz	1	1			1																																					
2003	Lake Placid	1							1				1																														
2004	Konigssee									1																																	
2005	Calgary	1										1							1																								
2007	St. Moritz			1	1													1																									
2008	Altenberg	1		1								1																															
2009	Lake Placid		1					1								1																											
2011	Konigssee	1	1							1																																	
2012	Lake Placid		1	1				1																																			
2013	St. Moritz	1								1		1																															
2015	Winterberg	1	1													1																											
2016	Igls		1			1								1																													
2017	Konigssee	2		1																																							
Totals (G, S, B)		25	20	17	13	15	11	7	4	7	0	3	1	1	0	2	1	1	2	0	0	0	1	0	1	0	4	5	3	7	2	0	1	0	0	0	0	0	0	2	0	0	0
Total Medals		**62**			**39**			**18**			**4**			**3**			**4**			**0**			**2**			**9**			**12**			**1**			**0**			**2**			**0**		
Weighted Point Totals		418			249			118			19			18			23			0			14			40			73			5			0			8			0		
		GER			**SUI**			**USA**			**RUS**			**LAT**			**CAN**			**GBR**			**FRA**			**AUT**			**ITA**			**BEL**			**ROU**			**SWE**			**ESP**		
*4-Man Bobsled Race was canceled due to the death of a German slider during a crash, after which the grieving team received a posthumous gold medal																																											
**4-Man Bobsled Race was canceled due to excessively warm conditions and melting track surface																																											

Data compiled from: https://en.wikipedia.org/wiki/FIBT_World_Championships. (Wikipedia, 2017b)

Table 2.11. World Championship 2-Man Bobsled Medal Results in the post-WWII era.

World Championship 2-Man Bobsled Results (post-WWII)

		GER			SUI			USA			RUS			LAT			CAN			GBR		
Year	Host City	G	S	B	G	S	B	G	S	B	G	S	B	G	S	B	G	S	B	G	S	B
1947	St. Moritz				1	1																
1949	Lake Placid				1	1				1												
1950	Cortina D'Ampezzo				1				1	1												
1951	Alpe d'Huez	1					1		1													
1953	Garmisch-Partenkirchen		1	1	1																	
1954	Cortina D'Ampezzo									1												
1955	St. Moritz				1		1															
1957	St. Moritz								1													
1958	Cortina D'Ampezzo																					
1959	St. Moritz									1												
1960	Cortina D'Ampezzo		1																			
1961	Lake Placid								1													
1962	Garmisch-Partenkirchen			1																		
1963	Igls																					1
1965	St. Moritz																		1	1		
1966	Cortina D'Ampezzo*																					1
1967	Alpe d'Huez**									1												
1969	Lake Placid																					
1970	St. Moritz	1	1				1															
1971	Cervinia																					
1973	Lake Placid	1				1																
1974	St. Moritz	1	1				1															
1975	Cervinia		1				1															
1977	St. Moritz			1	1	1																
1978	Lake Placid		1	1	1																	
1979	Konigssee		1	1	1																	
1981	Cortina D'Ampezzo	1	1		1																	
1982	St. Moritz			1	1	1																
1983	Lake Placid			1	1	1																
1985	Cervinia	1	1										1									
1986	Konigssee	1		1		1																
1987	St. Moritz			1	1	1																
1989	Cortina D'Ampezzo	1				1							1									
1990	St. Moritz		1	1	1																	
1991	Altenberg	1		1		1																
1993	Igls	1		1		1																
1995	Winterberg	1																1				
1996	Calgary	1					1											1				
1997	St. Moritz				1					1												
1999	Cortina D'Ampezzo		1																			
2000	Altenberg	1	1				1															
2001	St. Moritz	1				1	1															
2003	Lake Placid	1		1														1				
2004	Konigssee		1	1													1					
2005	Calgary		1				1										1					
2007	St. Moritz	1				1																
2008	Altenberg	1	1										1									
2009	Lake Placid		1		1					1												
2011	Konigssee		2								1											
2012	Lake Placid			1				1										1				
2013	St. Moritz	1		1		1																
2015	Winterberg	1	1												1							
2016	Igls	1	1				1															
2017	Konigssee	1		1														1				
Totals (G, S, B)		21	20	17	15	14	10	1	4	7	1	0	3	0	1	0	2	5	1	1	0	2
Total Medals		**58**			**39**			**12**			**4**			**1**			**8**			**3**		
Weighted Point Totals		378			260			58			22			5			49			18		
		GER			**SUI**			**USA**			**RUS**			**LAT**			**CAN**			**GBR**		

		FRA			AUT			ITA			BEL			ROU			SWE			ESP		
Year	Host City	G	S	B	G	S	B	G	S	B	G	S	B	G	S	B	G	S	B	G	S	B
1947	St. Moritz										1											
1949	Lake Placid																					
1950	Cortina D'Ampezzo																					
1951	Alpe d'Huez																					
1953	Garmisch-Partenkirchen																					
1954	Cortina D'Ampezzo							1	1													
1955	St. Moritz					1																
1957	St. Moritz							1														1
1958	Cortina D'Ampezzo						1	1	1													
1959	St. Moritz							1	1													
1960	Cortina D'Ampezzo							1		1												
1961	Lake Placid							1		1												
1962	Garmisch-Partenkirchen							1	1													
1963	Igls							1	1													
1965	St. Moritz								1													
1966	Cortina D'Ampezzo*							1	1													
1967	Alpe d'Huez**				1				1													
1969	Lake Placid							1		1					1							
1970	St. Moritz																					
1971	Cervinia						1	1	1													
1973	Lake Placid															1						
1974	St. Moritz																					
1975	Cervinia							1														
1977	St. Moritz																					
1978	Lake Placid																					
1979	Konigssee																					
1981	Cortina D'Ampezzo																					
1982	St. Moritz																					
1983	Lake Placid																					
1985	Cervinia																					
1986	Konigssee																					
1987	St. Moritz																					
1989	Cortina D'Ampezzo																					
1990	St. Moritz																					
1991	Altenberg																					
1993	Igls																					
1995	Winterberg			1																		
1996	Calgary																					
1997	St. Moritz								1													
1999	Cortina D'Ampezzo			1				1														
2000	Altenberg																					
2001	St. Moritz																					
2003	Lake Placid																					
2004	Konigssee																					
2005	Calgary																					
2007	St. Moritz									1												
2008	Altenberg																					
2009	Lake Placid																					
2011	Konigssee																					
2012	Lake Placid																					
2013	St. Moritz																					
2015	Winterberg																					
2016	Igls																					
2017	Konigssee																					
Totals (G, S, B)		0	0	2	1	1	2	13	10	4	1	0	0	0	1	1	0	0	0	0	0	1
Total Medals		**2**			**4**			**27**			**1**			**2**			**0**			**1**		
Weighted Point Totals		8			23			196			10			9			0			4		
		FRA			**AUT**			**ITA**			**BEL**			**ROU**			**SWE**			**ESP**		

*4-Man Bobsled Race was canceled due to the death of a German slider during a crash, after which the grieving team received a posthumous gold medal

**4-Man Bobsled Race was canceled due to excessively warm conditions and melting track surface

Data compiled from: https://en.wikipedia.org/wiki/FIBT_World_Championships. (Wikipedia, 2017b)

Table 2.12. Combined World Championship Bobsled Medal Results in the post-WWII era.

World Championship Combined Bobsled Results (post-WWII)																																											
		GER			SUI			USA			RUS			LAT			CAN			GBR			FRA			AUT			ITA			BEL			ROU			SWE			ESP		
Year	Host City	G	S	B	G	S	B	G	S	B	G	S	B	G	S	B	G	S	B	G	S	B	G	S	B	G	S	B	G	S	B	G	S	B	G	S	B	G	S	B	G	S	B
1947	St. Moritz				2	1																			1							1	1										
1949	Lake Placid				1	1	1	1	1	1																																	
1950	Cortina D'Ampezzo				1	1	1	1	1	1																																	
1951	Alpe d'Huez	2					2		2																																		
1953	Garmisch-Partenkirchen		2	2	1			1																																1			
1954	Cortina D'Ampezzo		1	1		1				1																			1	1													
1955	St. Moritz			1	2	1	1																				1																
1957	St. Moritz					1			1	1																			1	1													1
1958	Cortina D'Ampezzo	1	1																									1	1	1	1												
1959	St. Moritz			1				1		1																			1	2													
1960	Cortina D'Ampezzo		2				1																						1		2												
1961	Lake Placid								2																				2		1									1			
1962	Garmisch-Partenkirchen	1		1																								1	1	2													
1963	Igls																					1						1	2	2													
1965	St. Moritz									1							1		1	1										2													
1966	Cortina D'Ampezzo*	1																				1							1	1													
1967	Alpe d'Huez**									1																1				1													
1969	Lake Placid	1								1																			1	1	1					1							
1970	St. Moritz	1	2				2																						1														
1971	Cervinia			1	1																							1	1	2													
1973	Lake Placid	1		1	1	1																					1										1						
1974	St. Moritz	2	1			1	1																					1															
1975	Cervinia		2		1		1																					1	1														
1977	St. Moritz	1		2	1	2																																					
1978	Lake Placid	1	1	2	1	1																																					
1979	Konigssee	1	2	1	1		1																																				
1981	Cortina D'Ampezzo	2	1		1	1	1																																				
1982	St. Moritz		1	1	2	1	1																																				
1983	Lake Placid		1	2	2	1																																					
1985	Cervinia	2	2				1						1																														
1986	Konigssee	1		1	1	1	1																				1																
1987	St. Moritz		1	1	2	1	1																																				
1989	Cortina D'Ampezzo	1		1	1	2							1																														
1990	St. Moritz		2	1	2																							1															
1991	Altenberg	2		2		2																																					
1993	Igls	1		1	1	1				1																	1																
1995	Winterberg	2		1														1							1		1																
1996	Calgary	2		1		1	1											1																									
1997	St. Moritz	1	1		1			1		1																				1													
1999	Cortina D'Ampezzo		1			1													1				1		1				1														
2000	Altenberg	2	2			1	1																																				
2001	St. Moritz	2	1			2	1																																				
2003	Lake Placid	2		1					1				1					1																									
2004	Konigssee		1	1						1							1																										
2005	Calgary	1	1				1					1					1		1																								
2007	St. Moritz	1		1	1	1												1													1												
2008	Altenberg	2	1	1								1	1																														
2009	Lake Placid		2		1			1		1						1																											
2011	Konigssee	1	3							1	1																																
2012	Lake Placid		1	2				2										1																									
2013	St. Moritz	2		1		1				1		1																															
2015	Winterberg	2	2												1	1																											
2016	Igls	1	2			1	1							1																													
2017	Konigssee	3		2														1																									
	Totals (G, S, B)	46	40	34	28	29	21	8	8	14	1	3	4	1	1	2	3	6	3	1	0	2	1	0	3	1	5	7	16	17	6	1	1	0	0	1	1	0	0	2	0	0	1
	Total Medals	**120**			**78**			**30**			**8**			**4**			**12**			**3**			**4**			**13**			**39**			**2**			**2**			**2**			**1**		
	Weighted Point Totals	796			509			176			41			23			72			18			22			63			269			15			9			8			4		
		GER			SUI			USA			RUS			LAT			CAN			GBR			FRA			AUT			ITA			BEL			ROU			SWE			ESP		

*4-Man Bobsled Race was canceled due to the death of a German slider during a crash, after which the grieving team received a posthumous gold medal

**4-Man Bobsled Race was canceled due to excessively warm conditions and melting track surface

Table 2.13. World Cup Overall 4-Man Bobsled Medal Results in the post-WWII era.

World Cup Seasonal 4-Man Bobsled Results																															
		GER			SUI			USA			RUS			LAT			CAN			GBR			AUT			ITA			KOR		
Season Years		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1984	1985							1																							
1985	1986				1					1														1							
1986	1987		1					1																	1						
1987	1988			1																			2								
1988	1989					1																	1		1						
1989	1990			1								1					1														
1990	1991				1														1					1							
1991	1992	1				1																1									
1992	1993			1				1										1													
1993	1994		1																			1	1								
1994	1995			1													1				1										
1995	1996	1	1																1												
1996	1997		1		1																							1			
1997	1998	1				1																			1						
1998	1999	1		1		1																									
1999	2000				1										1				1												
2000	2001	1		1											1																
2001	2002		1		1		1																								
2002	2003	1					1								1																
2003	2004	1								1		1																			
2004	2005					1					1								1												
2005	2006						1				1							1													
2006	2007						1		1		1																				
2007	2008	1										1				1															
2008	2009			1							1				1																
2009	2010			1				1							1																
2010	2011	1							1				1																		
2011	2012		1	1							1																				
2012	2013			1							1				1																
2013	2014	1		1					1																						
2014	2015			1								1		1																	
2015	2016		1	1			1																								
2016	2017					1				1	1																				
Totals (1st, 2nd, 3rd)		10	7	13	5	6	5	4	3	3	7	4	1	1	6	1	2	2	4	0	1	2	4	2	3	0	0	1	0	0	0
Total "Top 3's"		30			16			10			12			8			8			3			9			1			0		
Weighted Point Totals		187			100			67			94			44			46			13			62			4			0		
		GER			SUI			USA			RUS			LAT			CAN			GBR			AUT			ITA			KOR		

Data compiled from: https://en.wikipedia.org/wiki/Bobsleigh_World_Cup. (Wikipedia, 2017a)

Table 2.14. World Cup Overall 2-Man Bobsled Medal Results in the post-WWII era.

World Cup Seasonal 2-Man Bobsled Results																															
		GER			SUI			USA			RUS			LAT			CAN			GBR			AUT			ITA			KOR		
Season Years		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1984	1985	1																													
1985	1986					1					1	1																			
1986	1987	1		1					1																						
1987	1988		1								1		1																		
1988	1989		1		1		1																								
1989	1990	1											1					1													
1990	1991	1				1													1												
1991	1992			1		1																				1					
1992	1993					1				1																1					
1993	1994		1														1											1			
1994	1995					1											1											1			
1995	1996	1		1														1													
1996	1997									1							1										1				
1997	1998															1		1									1				
1998	1999	1				1													1												
1999	2000				1	1	1																								
2000	2001		1	1	1																										
2001	2002				1		1											1													
2002	2003		1	1													1														
2003	2004	1		1														1													
2004	2005				1								1					1													
2005	2006									1		1					1														
2006	2007			1				1										1													
2007	2008	1				1							1																		
2008	2009		1	1	1																										
2009	2010		1	1	1																										
2010	2011		1								1																	1			
2011	2012		1		1								1																		
2012	2013			1											1		1														
2013	2014			1		1		1																							
2014	2015					1	1							1																	
2015	2016		1													1													1		
2016	2017	1							1																						1
Totals (1st, 2nd, 3rd)		9	10	11	8	10	4	2	2	3	3	2	5	1	1	2	6	7	2	0	0	0	0	0	0	2	2	3	1	0	1
Total "Top 3's"		**30**			**22**			**7**			**10**			**4**			**15**			**0**			**0**			**7**			**2**		
Weighted Point Totals		184			146			42			60			23			103			0			0			42			14		
		GER			**SUI**			**USA**			**RUS**			**LAT**			**CAN**			**GBR**			**AUT**			**ITA**			**KOR**		

Data compiled from: https://en.wikipedia.org/wiki/Bobsleigh_World_Cup. (Wikipedia, 2017a)

Table 2.15. World Cup Overall Combined Bobsled Medal Results in the post-WWII era.

World Cup Seasonal Combined Bobsled Results																															
		GER			SUI			USA			RUS			LAT			CAN			GBR			AUT			ITA			KOR		
Season Years		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1984	1985	1																													
1985	1986				1				1													1									
1986	1987		1	1				1																							
1987	1988			1								1											1								
1988	1989		1		1		1																								
1989	1990			2							1							1													
1990	1991			1		1													1					1							
1991	1992	1				1													1												
1992	1993					1		1																				1			
1993	1994																1					1		1							
1994	1995					1											1											1			
1995	1996	1																1	1												
1996	1997								1										1							1					
1997	1998															1	1										1				
1998	1999	1				1													1												
1999	2000				1	1													1												
2000	2001	1				1										1															
2001	2002			1	1	1																									
2002	2003	1	1				1																								
2003	2004	1								1								1													
2004	2005				1							1							1												
2005	2006									1		1					1														
2006	2007			1				1										1													
2007	2008	1								1		1																			
2008	2009			1		1					1																				
2009	2010			1		1		1																							
2010	2011	1								1		1																			
2011	2012	1		1								1																			
2012	2013			1								1		1																	
2013	2014						1	1				1																			
2014	2015		1										1	1																	
2015	2016	1	1				1																								
2016	2017	1								1		1																			
Totals (1st, 2nd, 3rd)		12	5	11	5	10	4	5	2	5	2	9	1	2	0	2	4	4	7	0	0	2	1	2	0	1	1	2	0	0	0
Total "Top 3's"		**28**			**19**			**12**			**12**			**4**			**15**			**2**			**3**			**4**			**0**		
Weighted Point Totals		189			116			80			69			28			88			8			20			23			0		
		GER			**SUI**			**USA**			**RUS**			**LAT**			**CAN**			**GBR**			**AUT**			**ITA**			**KOR**		

Data compiled from: https://en.wikipedia.org/wiki/Bobsleigh_World_Cup. (Wikipedia, 2017a)

Table 2.16. World Cup All-Time, All-Discipline, Bobsled Medal Results in the post-WWII era.

All-Time World Cup Seasonal Bobsled Results																															
		GER			SUI			USA			RUS			LAT			CAN			GBR			AUT			ITA			KOR		
Season Years		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1984	1985	2						1																							
1985	1986				2	1			1	1	1	1										1		1							
1986	1987	1	2	2				2	1																1						
1987	1988		1	2							1	1	1										3								
1988	1989		2		2	1	2																1		1						
1989	1990	1		3							1	1	1				1	2													
1990	1991	1		1	1	2													3					2							
1991	1992	2		1		3													1			1				1					
1992	1993			1		2		2		1								1								1		1			
1993	1994		2														2					2	1	1				1			
1994	1995			1		2											3				1							2			
1995	1996	3	1	1														2	2												
1996	1997		1		1				1	1							1		1							1	1	1			
1997	1998	1				1										2	1	1							1		2				
1998	1999	3		1		3													2												
1999	2000				3	2	1								1				2												
2000	2001	2	1	2	1	1									1	1															
2001	2002		1	1	3	1	2											1													
2002	2003	2	2	1			2								1		1														
2003	2004	3		1						2		1						2													
2004	2005				2	1					1	1	1					1	2												
2005	2006						1			2	1	2					2	1													
2006	2007			2			1	2	1		1							2													
2007	2008	3				1				1		2	1			1															
2008	2009		1	3	1	1					2				1																
2009	2010		1	3	1	1		2							1																
2010	2011	2	1						1	1	1	1	1															1			
2011	2012	1	2	2	1						1	1	1																		
2012	2013			3							1	1		1	2		1														
2013	2014	1		2		1	1	2	1			1																			
2014	2015		1	1		1	1					1	1	3																	
2015	2016	1	3	1			2									1													1		
2016	2017	2				1			1	2	1	1																			1
Totals (1st, 2nd, 3rd)		31	22	35	18	26	13	11	7	11	12	15	7	4	7	5	12	13	13	0	1	4	5	4	3	3	3	6	1	0	1
Total "Top 3's"		88			57			29			34			16			38			5			12			12			2		
Weighted Point Totals		560			362			189			223			95			237			21			82			69			14		
		GER			SUI			USA			RUS			LAT			CAN			GBR			AUT			ITA			KOR		

Data compiled from: https://en.wikipedia.org/wiki/Bobsleigh_World_Cup. (Wikipedia, 2017a)

Appendix B

Effect Size Tables for Push Rank Group Comparisons of Combine Metrics

Table 4.3. 2014 PPC group mean differences. *Italics* indicates .05 < p < .10. **Bold** indicates p < .05. **Bold and underlined** indicates p < .01.

Compared Groups		15m (s)			30m (s)			60m (s)		
1	2	ES (*d*)	p	$\Delta\bar{x}$	ES (*d*)	p	$\Delta\bar{x}$	ES (*d*)	p	$\Delta\bar{x}$
TOP5	2ND-5	-.71	.316	-.04	-.67	.337	-.05	-.67	.325	-.11
TOP5	ALL	-.79	.173	-.04	-.97	.115	-.04	-.88	.168	-.14
TOP5	NOTTOP5	-1.17	*.061*	-.06	-1.44	**.029**	-.11	-1.21	*.071*	-.20
TOP5	NOTTOP10	-1.44	**.039**	-.08	-2.08	**.007**	-.15	-1.53	**.035**	-.25
2ND-5	NOTTOP10	-.65	.330	-.04	-1.22	*.085*	-.10	-.67	.317	-.14
TOP10	ALL	-.46	.297	-.03	-.66	.144	-.06	-.49	.270	-.09
TOP10	NOTTOP10	-1.06	*.053*	-.06	-1.66	**.005**	-.13	-1.08	**.045**	-.20
Compared Groups		30f (s)			SBJ (m)			UST (m)		
1	2	ES (*d*)	p	$\Delta\bar{x}$	ES (*d*)	p	$\Delta\bar{x}$	ES (*d*)	p	$\Delta\bar{x}$
TOP5	2ND-5	-.37	.576	-.03	.52	.475	.07	.00	.995	.00
TOP5	ALL	-.72	.248	-.06	.67	.212	.11	.51	.330	.55
TOP5	NOTTOP5	-.97	.136	-.08	1.02	*.078*	.17	.76	.174	.80
TOP5	NOTTOP10	-1.37	*.053*	-.11	1.33	*.078*	.22	1.37	**.035**	1.25
2ND-5	NOTTOP10	-.68	.294	-.08	1.03	.311	.15	1.38	**.043**	1.25
TOP10	ALL	-.45	.306	-.04	.52	.243	.08	.53	.222	.55
TOP10	NOTTOP10	-1.02	*.060*	-.10	1.22	**.028**	.19	1.44	**.014**	1.25
Compared Groups		1RM PC (kg)			3-ITEM (points)			6-ITEM (points)		
1	2	ES (*d*)	p	$\Delta\bar{x}$	ES (*d*)	p	$\Delta\bar{x}$	ES (*d*)	p	$\Delta\bar{x}$
TOP5	2ND-5	.78	.252	8.0	-.05	.115	0	.66	.351	20
TOP5	ALL	.82	.177	9.3	-.08	*.074*	0	.98	.114	35
TOP5	NOTTOP5	1.27	*.056*	14.0	-.11	*.082*	0	1.44	**.027**	50
TOP5	NOTTOP10	2.15	**.013**	20.0	-.15	*.091*	0	2.11	**.006**	67
2ND-5	NOTTOP10	1.39	*.073*	12.0	-.10	.120	0	1.32	*.066*	46
TOP10	ALL	.49	.269	5.3	-.06	*.070*	0	.71	.136	26
TOP10	NOTTOP10	1.74	**.007**	16.0	-.13	*.086*	0	1.74	**.004**	58
Compared Groups		BM (kg)			Age (years)					
1	2	ES (*d*)	p	$\Delta\bar{x}$	ES (*d*)	p	$\Delta\bar{x}$			
TOP5	2ND-5	.03	.962	0.2	.31	.654	0.6			
TOP5	ALL	.21	.707	1.5	.48	.382	1.0			
TOP5	NOTTOP5	.28	.627	2.2	.68	.243	1.5			
TOP5	NOTTOP10	.41	.511	3.3	.88	.174	2.0			
2ND-5	NOTTOP10	.34	.605	3.0	.56	.405	1.3			
TOP10	ALL	.18	.447	1.4	.34	.429	0.7			
TOP10	NOTTOP10	.39	.447	3.2	.75	.154	1.7			

Table 4.4. 2015 PPC group mean differences. *Italics* indicates .05 < p < .10. **Bold** indicates p < .05. **Bold and underlined** indicates p < .01.

Compared Groups		15 m (s)			30 m (s)			60 m (s)		
1	2	ES (*d*)	p	$\Delta\bar{x}$	ES (*d*)	p	$\Delta\bar{x}$	ES	p	$\Delta\bar{x}$
TOP5	2ND-5	.12	.858	.01	-.07	.918	-.01	-.06	.926	-.01
TOP5	ALL	.05	.928	.00	-.20	.692	.00	-.23	.655	-.04
TOP5	NOTTOP5	.07	.901	.00	-.30	.578	-.02	-.38	.507	-.06
TOP5	NOTTOP10	.00	1.00	.00	-.62	.358	-.04	-.96	.251	-.15
2ND-5	NOTTOP10	-.13	.839	-.01	-.48	.472	-.04	-.99	.230	-.14
TOP10	ALL	-.02	.956	.00	-.16	.690	-.01	-.22	.610	-.03
TOP10	NOTTOP10	-.08	.901	.00	-.57	.361	-.04	-1.01	.166	-.15
Compared Groups		30-m Fly (s)			Broad Jump (m)			Shot Toss (m)		
1	2	ES (*d*)	p	$\Delta\bar{x}$	ES (*d*)	p	$\Delta\bar{x}$	ES	p	$\Delta\bar{x}$
TOP5	2ND-5	-.23	.725	-.02	-.20	.755	-.04	.45	.497	.45
TOP5	ALL	-.36	.476	-.03	.30	.548	.06	.79	.203	.79
TOP5	NOTTOP5	-.56	.296	-.05	.47	.377	.09	1.18	*.079*	1.24
TOP5	NOTTOP10	-.94	.177	-.07	1.23	.389	.23	3.55	**.001**	2.22
2ND-5	NOTTOP10	-.80	.244	-.05	2.72	.134	.26	1.82	**.035**	1.78
TOP10	ALL	-.26	.523	-.02	.46	.281	.08	.51	.244	.57
TOP10	NOTTOP10	-.90	.147	-.06	1.72	**.012**	.24	2.49	**.002**	2.00
Compared Groups		Clean 1RM (kg)			Back Squat 3RM					
1	2	ES (*d*)	p	$\Delta\bar{x}$	ES (*d*)	p	$\Delta\bar{x}$			
TOP5	2ND-5	1.20	.129	9.3	2.99	**.004**	25.5			
Compared Groups		3-Item Score (points)			8-Item Score					
1	2	ES (*d*)	p	$\Delta\bar{x}$	ES (*d*)	p	$\Delta\bar{x}$			
TOP5	2ND-5	-.03	.968	0	.33	.638	10			
Compared Groups		6-Item Score (points)			Body Mass (kg)			Age (years)		
1	2	ES (*d*)	p	$\Delta\bar{x}$	ES (*d*)	p	$\Delta\bar{x}$	ES	p	$\Delta\bar{x}$
TOP5	2ND-5	.08	.898	3	.94	.175	4.6	-.79	.246	-2.4
TOP5	ALL	.46	.436	15	1.05	*.078*	8.2	-.26	.650	-0.6
TOP5	NOTTOP5	.65	.269	21	1.50	**.017**	11.1	-.37	.552	-1.0
TOP5	NOTTOP10	1.64	**.049**	45	2.01	**.005**	14.7	.54	.467	0.8
2ND-5	NOTTOP10	1.59	*.053*	42	1.54	**.028**	10.1	1.15	.150	3.2
TOP10	ALL	.44	.355	14	.78	**.001**	5.9	.19	.643	0.6
TOP10	NOTTOP10	1.67	**.021**	44	1.76	**.001**	12.4	.88	.241	2.0

Table 4.5. 2014 NPC group mean differences. *Italics* indicates .05 < p < .10. **Bold** indicates p < .05. <u>**Bold and underlined**</u> indicates p < .01.

Compared Groups 1	Compared Groups 2	15 m (s) ES (*d*)	p	Δx̄	30 m (s) ES	p	Δx̄	60 m (s) ES	p	Δx̄
TOP5	2ND-5	-1.11	.119	-.05	-.52	.433	-.04	1.03	.344	.08
TOP5	ALL	-.79	.169	-.04	-.70	.249	-.04	-.53	.652	-.06
TOP5	NOTTOP5	-1.07	*.052*	-.05	-.93	.122	-.07	-.64	.593	-.08
TOP5	NOTTOP10	-1.04	.110	-.05	-1.09	*.097*	-.08	-1.01	.363	-.12
2ND-5	NOTTOP10	.05	.631	.00	-.60	.394	-.04	-1.70	.209	-.20
TOP10	ALL	-.27	.699	-.01	-.47	.385	-.04	-.80	.321	-.10
TOP10	NOTTOP10	-.50	.475	-.02	-.86	.119	-.06	-1.28	.141	-.16

Compared Groups 1	Compared Groups 2	30-m Fly (s) ES (*d*)	p	Δx̄	Broad Jump (m) ES	p	Δx̄	Shot Toss (m) ES	p	Δx̄
TOP5	2ND-5	1.20	.232	.09	.79	.486	.12	.23	.809	.30
TOP5	ALL	-.28	.822	-.02	.51	.489	.08	.55	.531	.60
TOP5	NOTTOP5	-.32	.793	-.02	.69	.353	.11	.74	.413	.79
TOP5	NOTTOP10	-.80	.397	-.05	.66	.357	.11	.87	.367	.91
2ND-5	NOTTOP10	-1.57	.120	-.14	-.06	.947	-.01	.51	.656	.61
TOP10	ALL	-.66	.330	-.05	.26	.747	.04	.46	.577	.48
TOP10	NOTTOP10	-1.12	.125	-.09	.43	.617	.06	.78	.371	.79

Compared Groups 1	Compared Groups 2	Power Clean 1RM ES (*d*)	p	Δx̄	6-Item Score ES	p	Δx̄	3-Item Score ES	p	Δx̄
TOP5	2ND-5	1.38	*.084*	5.8	-.18	.860	-2	1.93	**.050**	20
TOP5	ALL	1.32	*.056*	10.8	.17	.375	6	1.14	<u>**.003**</u>	15
TOP5	NOTTOP5	2.07	<u>**.004**</u>	14.2	1.23	.292	41	1.91	<u>**.003**</u>	20
TOP5	NOTTOP10	2.57	<u>**.001**</u>	17.0	1.48	.205	49	1.88	<u>**.009**</u>	21
2ND-5	NOTTOP10	1.47	*.084*	11.3	1.55	.277	51	.07	1.00	1
TOP10	ALL	.96	*.090*	8.3	.20	.235	6	.52	.315	7
TOP10	NOTTOP10	2.05	<u>**.001**</u>	14.4	1.52	*.094*	50	1.08	*.067*	13

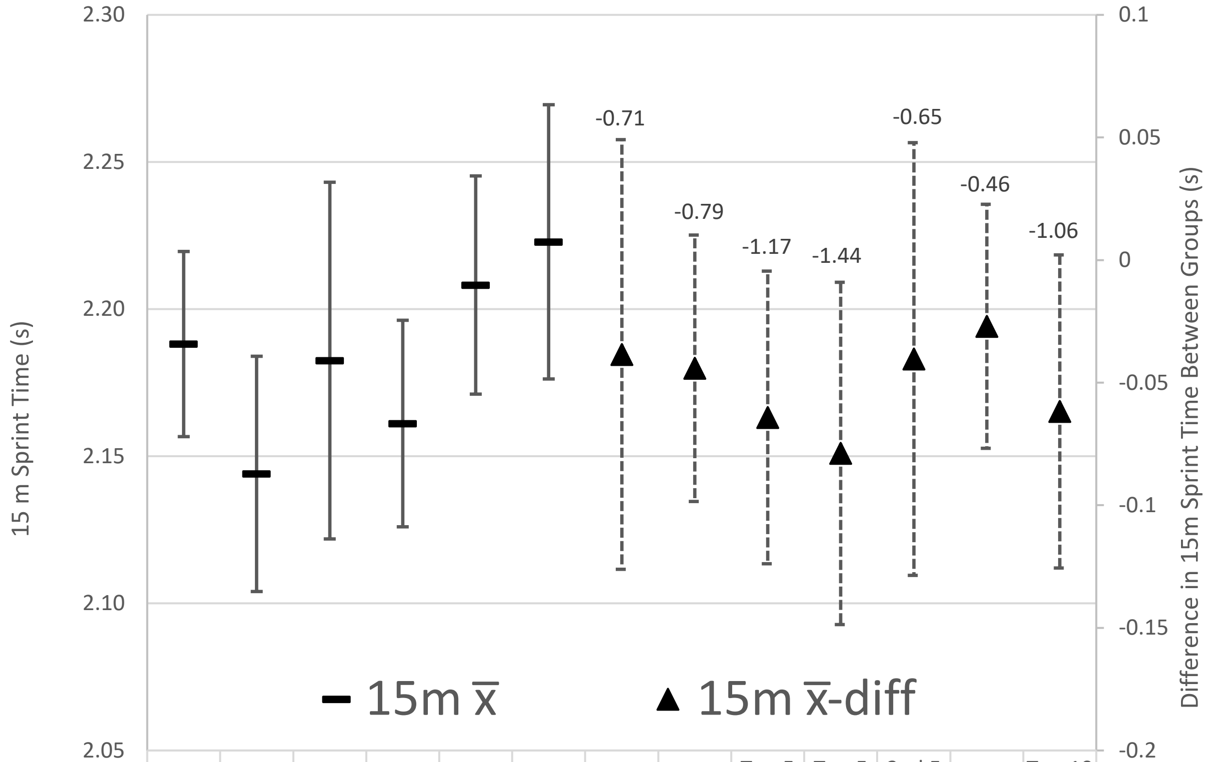
Compared Groups 1	Compared Groups 2	Body Mass (kg) ES (*d*)	p	Δx̄	Age (years) ES	p	Δx̄
TOP5	2ND-5	1.06	.152	7.0	.84	.219	1.4
TOP5	ALL	.85	.225	5.6	.77	.203	1.2
TOP5	NOTTOP5	1.15	.109	7.4	.95	.115	1.5
TOP5	NOTTOP10	1.14	.170	7.5	.95	.113	1.6
2ND-5	NOTTOP10	.06	.745	0.5	.09	.688	0.2
TOP10	ALL	.35	.482	2.5	.27	.459	0.5
TOP10	NOTTOP10	.61	.482	4.4	.46	.212	0.9

Table 4.6. 2015 NPC group mean differences. *Italics* indicates .05 < p < .10. **Bold** indicates p < .05. **Bold and underlined** indicates p < .01.

Compared Groups		15 m (s)			30 m (s)			60 m (s)					
1	2	ES (*d*)	p	$\Delta\bar{x}$	ES (*d*)	p	$\Delta\bar{x}$	ES (*d*)	p	$\Delta\bar{x}$			
TOP5	2ND-5	.27	.684	.01	-.12	.859	-.01	-1.40	.158	-.22			
TOP5	ALL	.18	.723	.01	-.18	.719	.01	-.63	.306	-.10			
TOP5	NOTTOP5	.23	.653	.01	-.24	.653	-.02	-.86	.189	-.13			
TOP5	NOTTOP10	.22	.704	.01	-.29	.607	-.03	-.72	.278	-.11			
2ND-5	NOTTOP10	.00	1.00	.00	-.18	.755	-.02	.62	.442	.11			
TOP10	ALL	.06	.872	.00	-.13	.750	-.01	-.20	.781	-.03			
TOP10	NOTTOP10	.12	.796	.01	-.24	.597	-.02	-.29	.680	-.05			
Compared Groups		30-m Fly (s)			Broad Jump (m)			Shot Toss (m)					
1	2	ES (*d*)	p	$\Delta\bar{x}$	ES (*d*)	p	$\Delta\bar{x}$	ES (*d*)	p	$\Delta\bar{x}$			
TOP5	2ND-5	-1.46	.175	-.14	.37	.663	.10	.22	.835	.19			
TOP5	ALL	-.81	.157	-.08	.24	.653	.05	.47	.438	.54			
TOP5	NOTTOP5	-1.16	*.050*	-.11	.33	.562	.07	.61	.334	.72			
TOP5	NOTTOP10	-1.08	*.079*	-.10	-.20	.601	.06	.67	.309	.83			
2ND-5	NOTTOP10	.46	.550	.04	-.55	.831	-.04	.62	.546	.65			
TOP10	ALL	-.32	.499	-.03	.08	.863	.02	.45	.400	.48			
TOP10	NOTTOP10	-.53	.299	-.05	-.36	.796	.03	.66	.247	.77			
Compared Groups		1RM PC (kg)			3RM BS (kg)			8-ITEM (points)					
1	2	ES (*d*)	p	$\Delta\bar{x}$	ES (*d*)	p	$\Delta\bar{x}$	ES (*d*)	p	$\Delta\bar{x}$			
TOP5	2ND-5	.29	.685	1.5	.50	.456	5.5	.67	.499	23			
TOP5	ALL	.91	.180	6.9	.86	.186	9.8	.57	.400	18			
TOP5	NOTTOP5	1.18	*.097*	9.0	1.13	*.094*	13.8	.57	.305	18			
TOP5	NOTTOP10	1.93	**.017**	13.8	1.46	**.042**	18.0	.70	.336	23			
2ND-5	NOTTOP10	1.68	**.018**	12.3	.78	.240	12.5	.00	1.00	0			
TOP10	ALL	.80	*.087*	6.1	.56	.215	7.3	.28	.609	9			
TOP10	NOTTOP10	1.81	**.002**	12.9	1.12	**.034**	15.6	.42	.478	14			
Compared Groups		6-Item Score			3-Item Score			Body Mass (kg)			Age (years)		
1	2	ES (*d*)	p	$\Delta\bar{x}$	ES (*d*)	p	$\Delta\bar{x}$	ES (*d*)	p	$\Delta\bar{x}$	ES (*d*)	p	$\Delta\bar{x}$
TOP5	2ND-5	.61	.460	22	-.10	.878	-2	-.34	.648	-4.3	1.03	.143	2.2
TOP5	ALL	.40	.520	12	.17	.753	3	.21	.693	3.0	.28	.618	0.7
TOP5	NOTTOP5	.51	.435	16	.22	.693	4	.28	.620	3.9	.33	.561	0.8
TOP5	NOTTOP10	.47	.843	15	.41	.521	7	.54	.380	7.6	.13	.820	0.3
2ND-5	NOTTOP10	-.16	.829	-7	.56	.361	9	1.01	.144	11.8	-.68	.240	-1.9
TOP10	ALL	.15	.763	5	.25	.557	4	.41	.136	5.1	-.17	.661	-0.4
TOP10	NOTTOP10	.23	.676	8	.50	.314	8	.77	.136	9.7	-.28	.521	-0.8

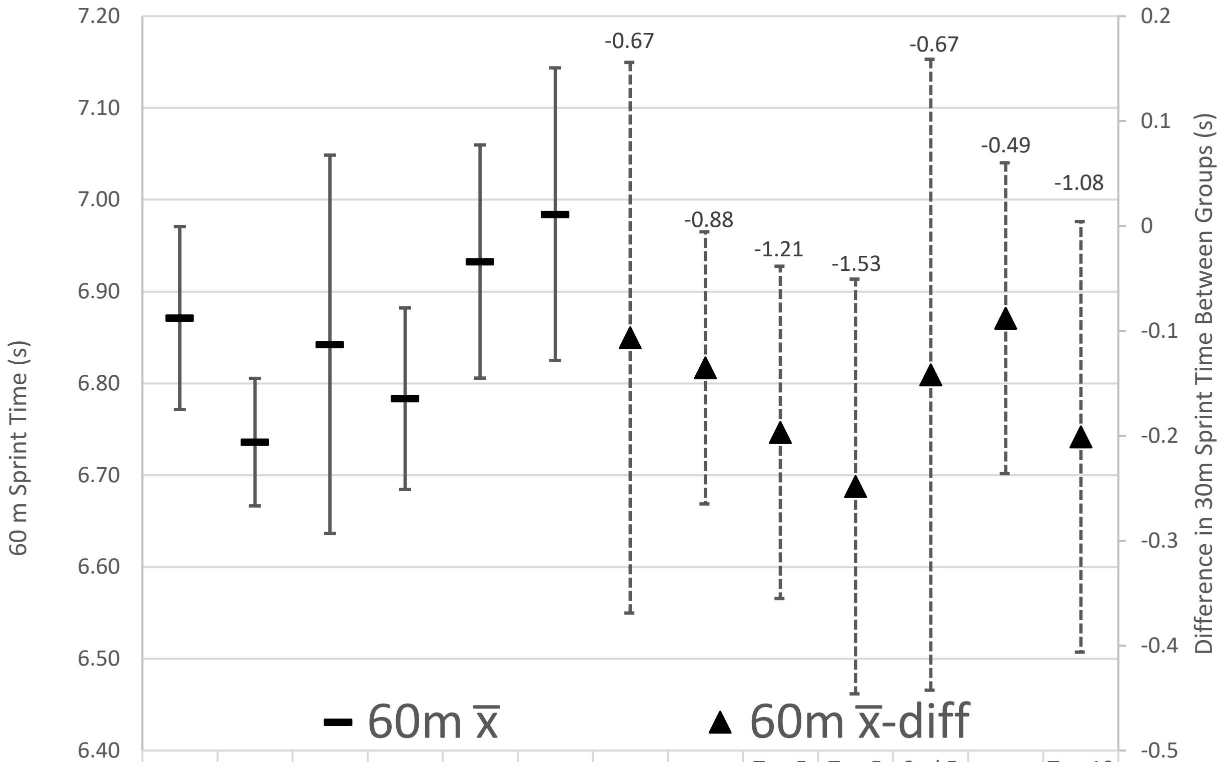
Appendix C

Ancillary Group Mean Comparisons for 2014 PPC



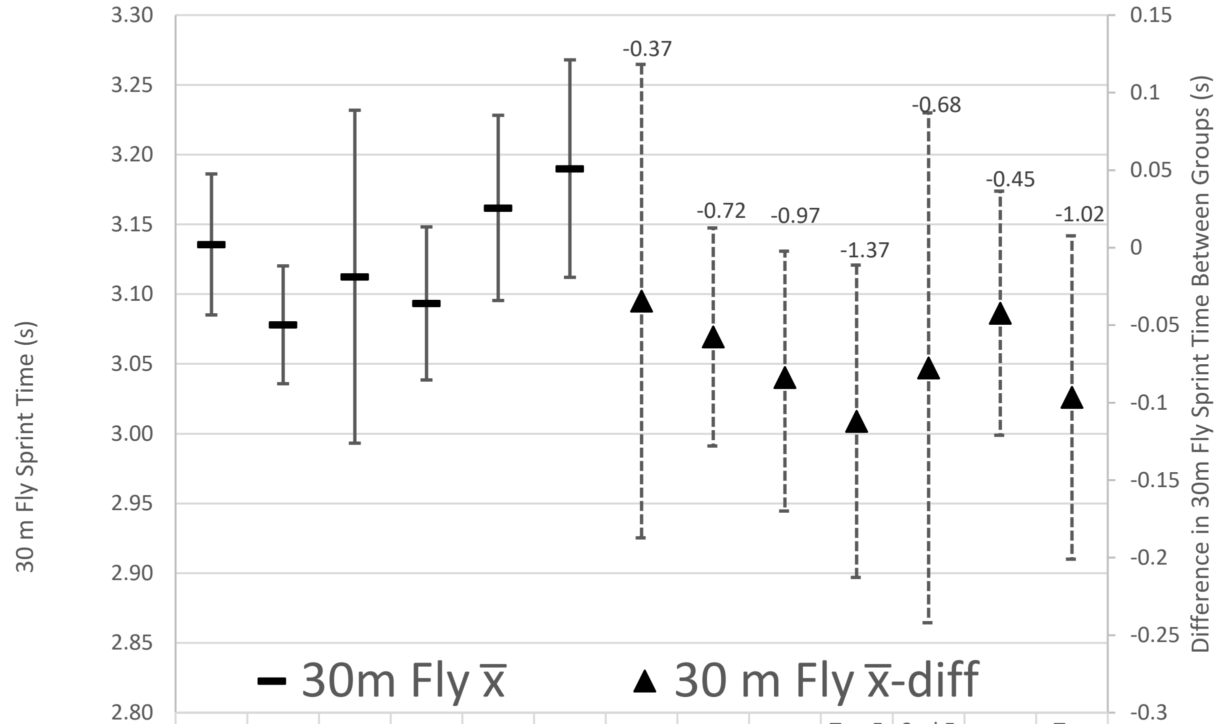
	All Athletes	Top 5	Second 5	Top 10	All But Top 5	All But Top 10	Top 5 vs. 2nd 5	Top 5 vs All	Top 5 vs. All But Top 5	Top 5 vs. All But Top 10	2nd 5 vs. All But Top 10	Top 10 vs. All	Top 10 vs. All But Top 10
15m x̄	2.19	2.14	2.18	2.16	2.21	2.22							
15m x̄-diff							-0.04	-0.04	-0.064	-0.08	-0.04	-0.03	-0.06

Figure 4.20. PPC 2014, 15-m Sprint times for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.



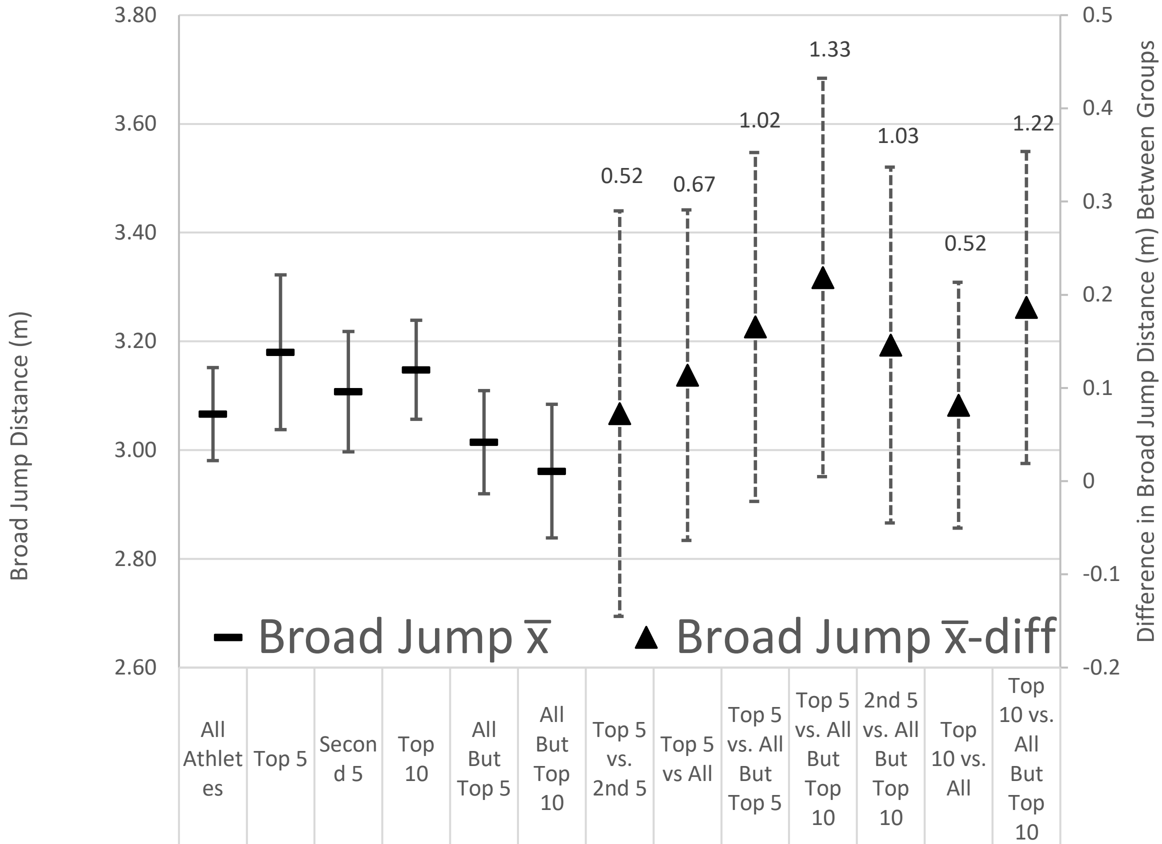
	All Athletes	Top 5	Second 5	Top 10	All But Top 5	All But Top 10	Top 5 vs. 2nd 5	Top 5 vs All	Top 5 vs. All But Top 5	Top 5 vs. All But Top 10	2nd 5 vs. All But Top 10	Top 10 vs. All	Top 10 vs. All But Top 10
60m x̄	6.87	6.74	6.84	6.78	6.93	6.98							
60m x̄-diff							-0.11	-0.14	-0.197	-0.25	-0.14	-0.09	-0.20

Figure 4.21. PPC 2014, 60-m Sprint times for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.



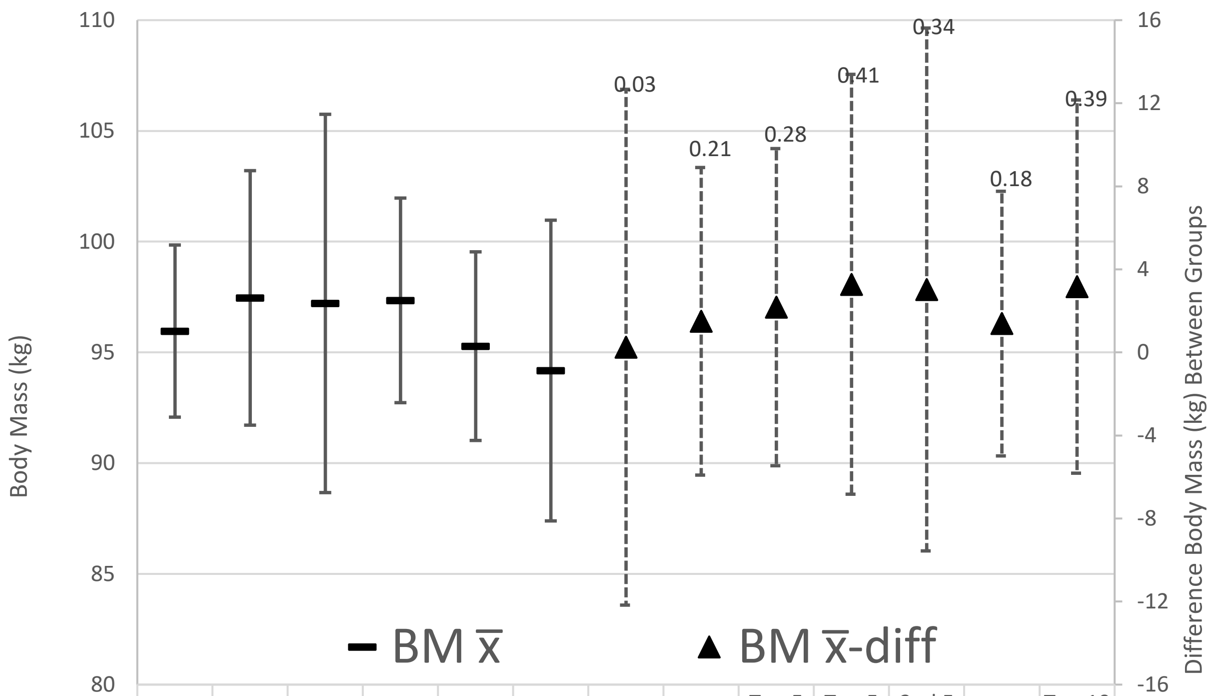
	All Athletes	Top 5	Second 5	Top 10	All But Top 5	All But Top 10	Top 5 vs. 2nd 5	Top 5 vs All	Top 5 vs. All But Top 5	Top 5 vs. All But Top 10	2nd 5 vs. All But Top 10	Top 10 vs. All	Top 10 vs. All But Top 10
30m Fly x̄	3.14	3.08	3.11	3.09	3.16	3.19							
30 m Fly x̄-diff							-0.03	-0.06	-0.084	-0.11	-0.08	-0.04	-0.10

Figure 4.22. PPC 2014, 30-m Fly times for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.



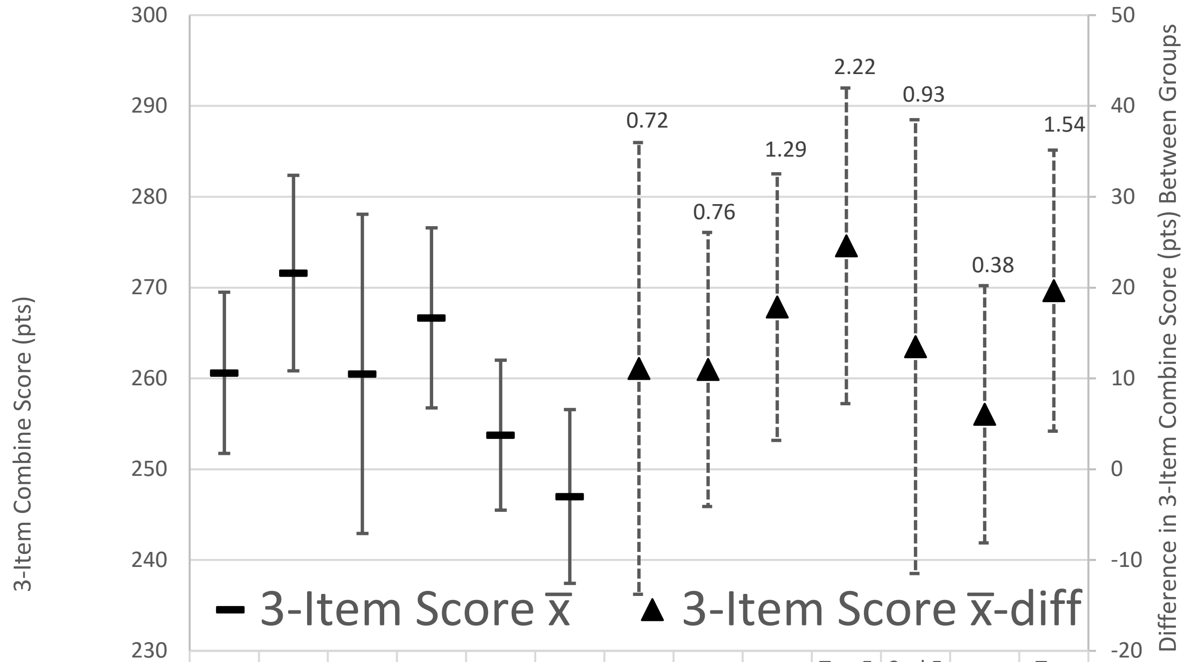
	All Athletes	Top 5	Second 5	Top 10	All But Top 5	All But Top 10	Top 5 vs. 2nd 5	Top 5 vs All	Top 5 vs. All But Top 5	Top 5 vs. All But Top 10	2nd 5 vs. All But Top 10	Top 10 vs. All	Top 10 vs. All But Top 10
Broad Jump x̅	3.07	3.18	3.11	3.15	3.01	2.96							
Broad Jump x̅-diff							0.07	0.11	0.165	0.22	0.15	0.08	0.19

Figure 4.23. PPC 2014, Broad jump distances for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.



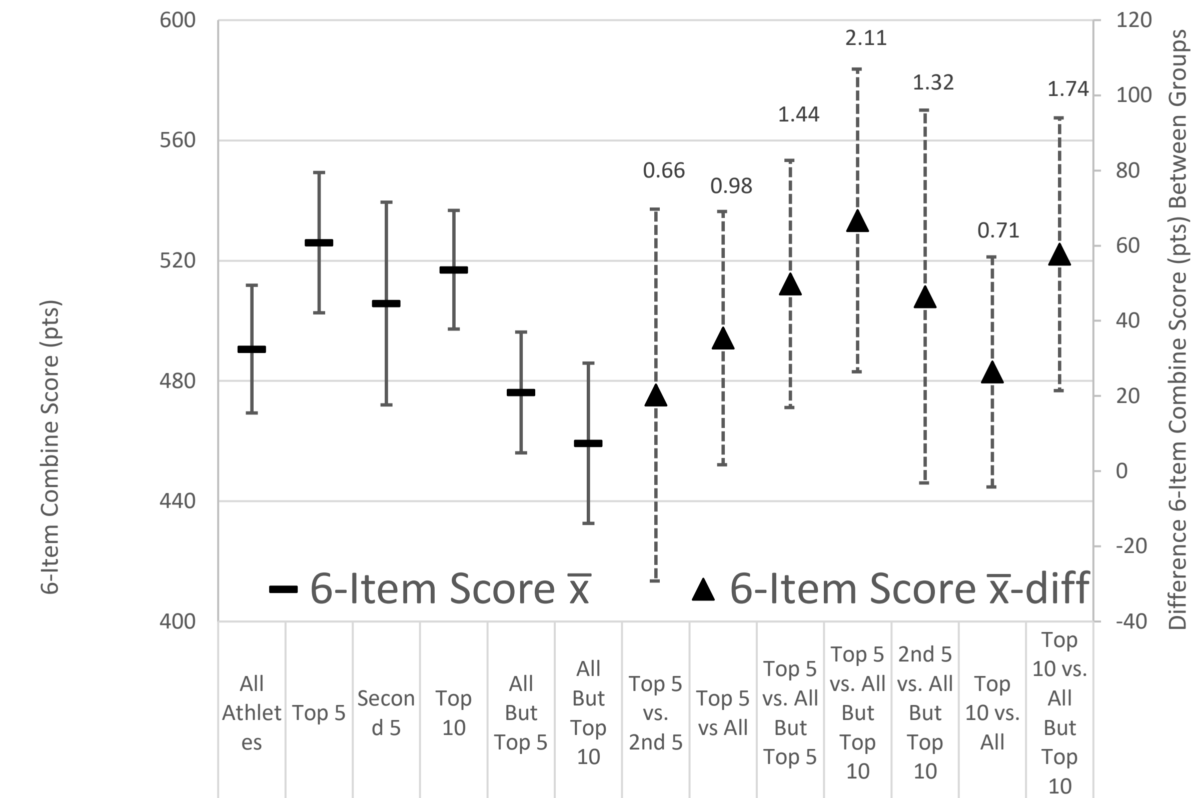
	All Athletes	Top 5	Second 5	Top 10	All But Top 5	All But Top 10	Top 5 vs. 2nd 5	Top 5 vs All	Top 5 vs. All But Top 5	Top 5 vs. All But Top 10	2nd 5 vs. All But Top 10	Top 10 vs. All	Top 10 vs. All But Top 10
BM x̄	95.96	97.46	97.21	97.35	95.28	94.18							
BM x̄-diff							0.25	1.50	2.18	3.28	3.03	1.39	3.17

Figure 4.24. PPC 2014, Body mass for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.



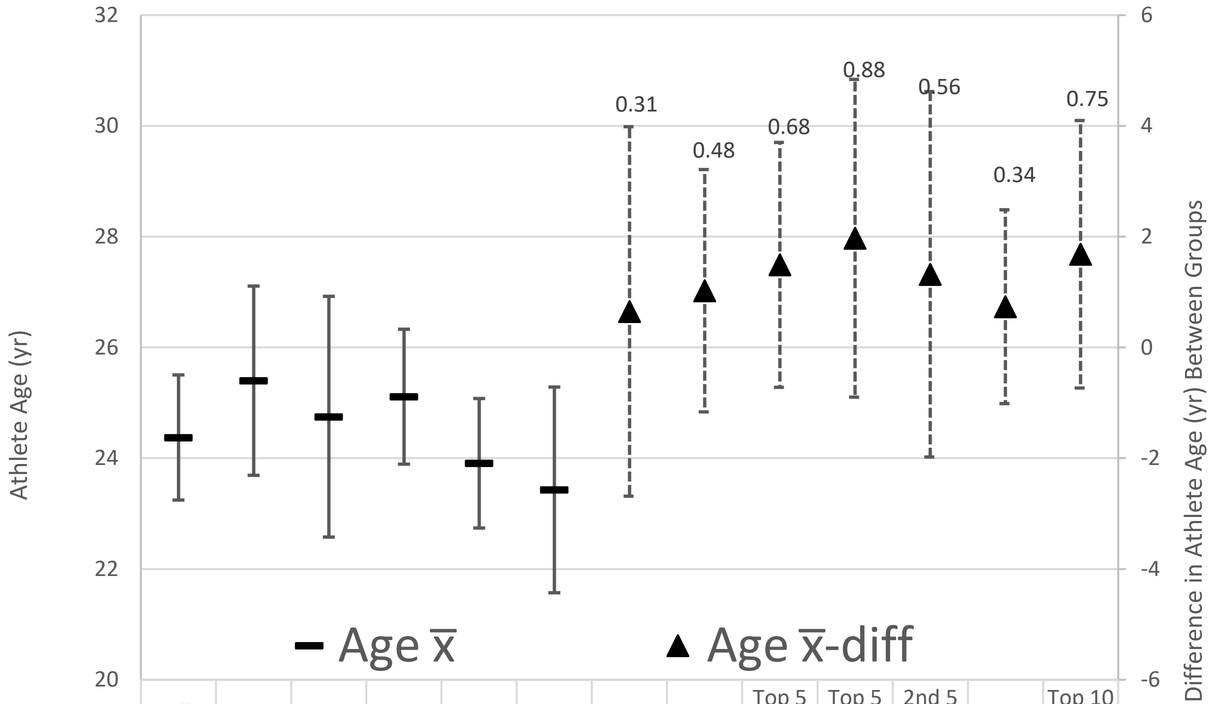
	All Athletes	Top 5	Second 5	Top 10	All But Top 5	All But Top 10	Top 5 vs. 2nd 5	Top 5 vs All	Top 5 vs. All But Top 5	Top 5 vs. All But Top 10	2nd 5 vs. All But Top 10	Top 10 vs. All	Top 10 vs. All But Top 10
3-Item Score x̄	260.62	271.60	260.50	266.67	253.75	247.00							
3-Item Score x̄-diff							11.10	10.98	17.850	24.60	13.50	6.05	19.67

Figure 4.25. PPC 2014, 3-Item combine scores for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.



	All Athletes	Top 5	Second 5	Top 10	All But Top 5	All But Top 10	Top 5 vs. 2nd 5	Top 5 vs All	Top 5 vs. All But Top 5	Top 5 vs. All But Top 10	2nd 5 vs. All But Top 10	Top 10 vs. All	Top 10 vs. All But Top 10
6-Item Score x̄	490.60	526.00	505.75	517.00	476.18	459.29							
▲ 6-Item Score x̄-diff							20.25	35.40	49.818	66.71	46.46	26.40	57.71

Figure 4.26. PPC 2014, 6-Item combine scores for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.

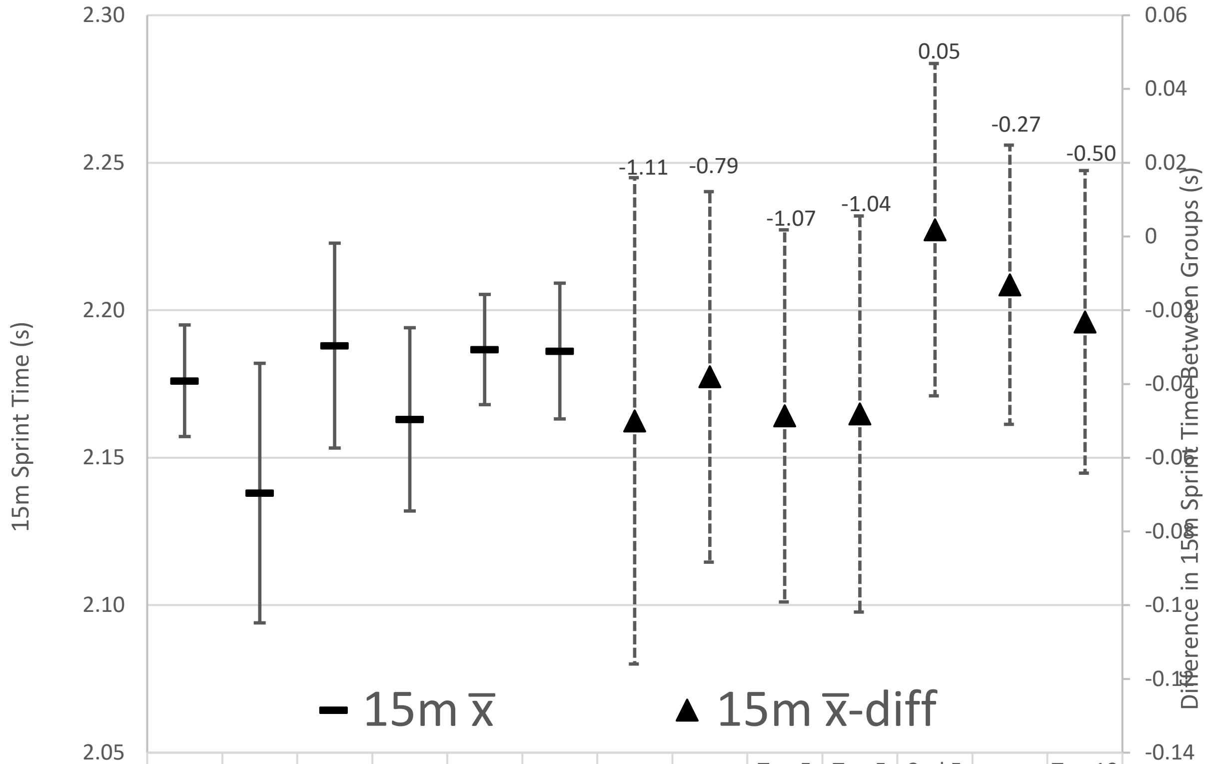


	All Athletes	Top 5	Second 5	Top 10	All But Top 5	All But Top 10	Top 5 vs. 2nd 5	Top 5 vs All	Top 5 vs. All But Top 5	Top 5 vs. All But Top 10	2nd 5 vs. All But Top 10	Top 10 vs. All	Top 10 vs. All But Top 10
Age x̄	24.38	25.40	24.75	25.11	23.91	23.43							
Age x̄-diff							0.65	1.03	1.491	1.97	1.32	0.74	1.68

Figure 4.27. PPC 2014, Athlete age for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.

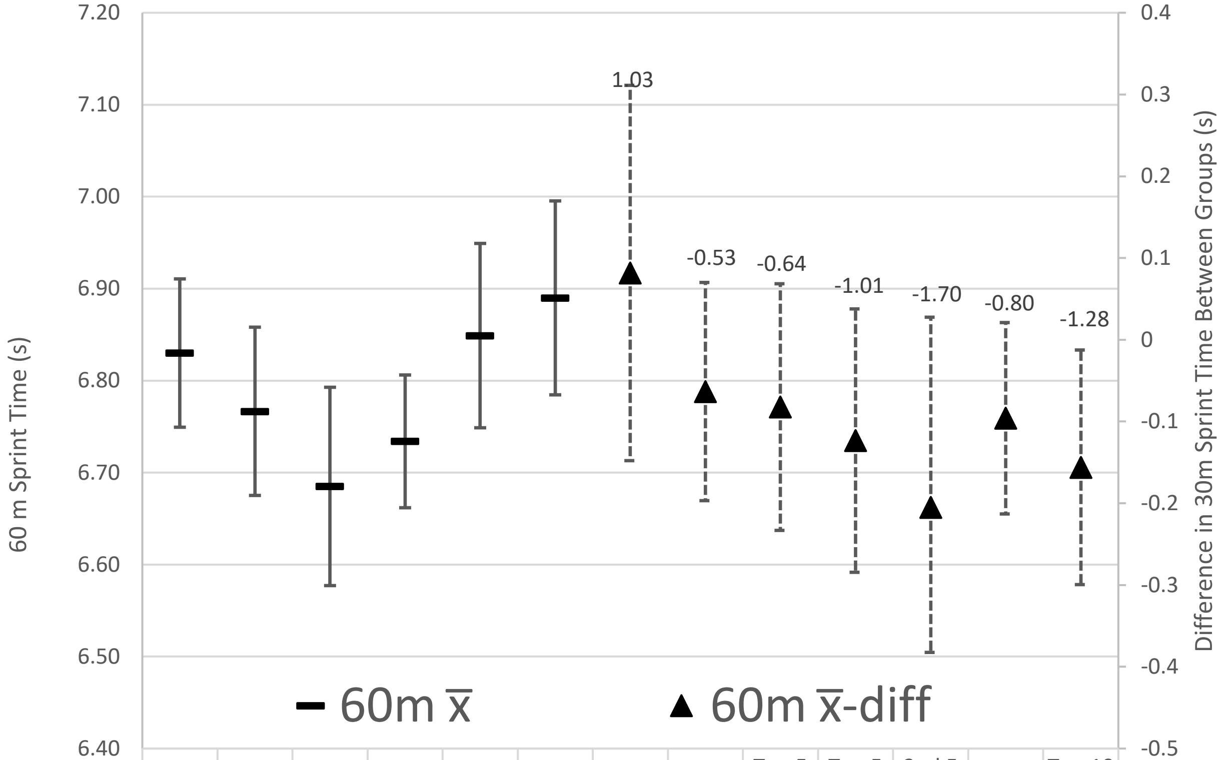
Appendix D

Ancillary Group Mean Comparisons for 2014 NPC



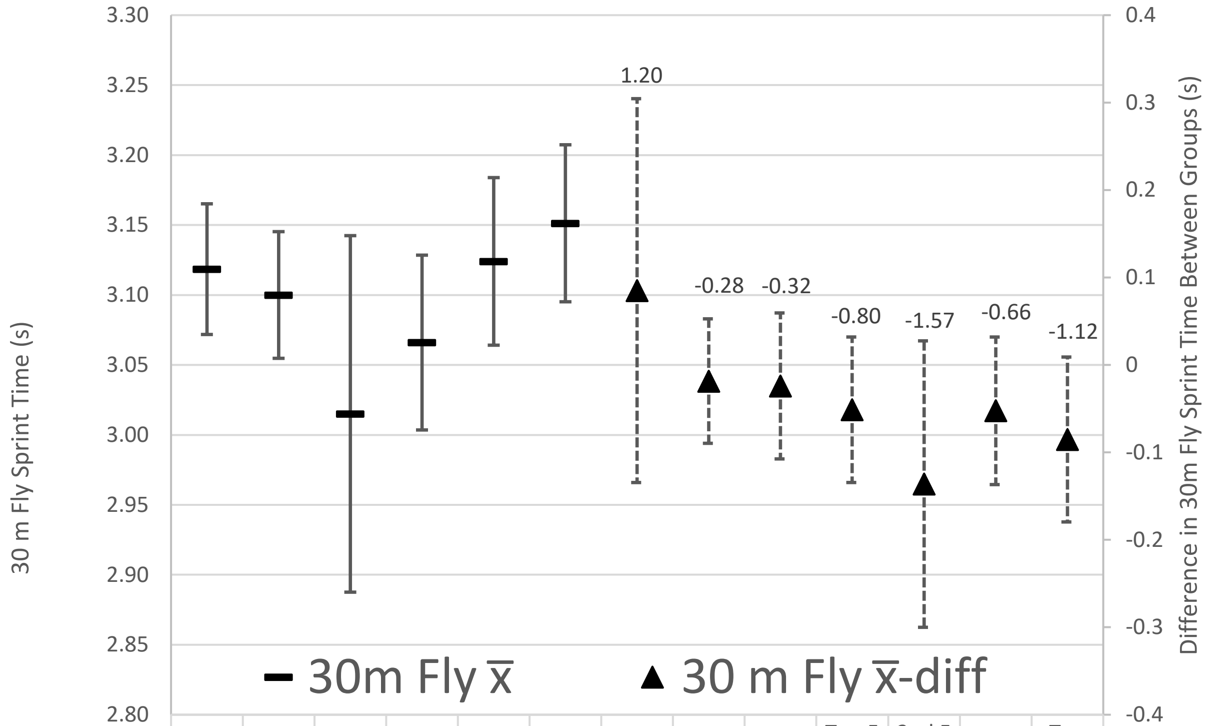
	All Athletes	Top 5	Second 5	Top 10	All But Top 5	All But Top 10	Top 5 vs. 2nd 5	Top 5 vs All	Top 5 vs. All But Top 5	Top 5 vs. All But Top 10	2nd 5 vs. All But Top 10	Top 10 vs. All	Top 10 vs. All But Top 10
15m x̄	2.18	2.14	2.19	2.16	2.19	2.19							
15m x̄-diff							-0.05	-0.04	-0.049	-0.05	0.00	-0.01	-0.02

Figure 4.28. NPC 2014, 15-m Sprint times for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.



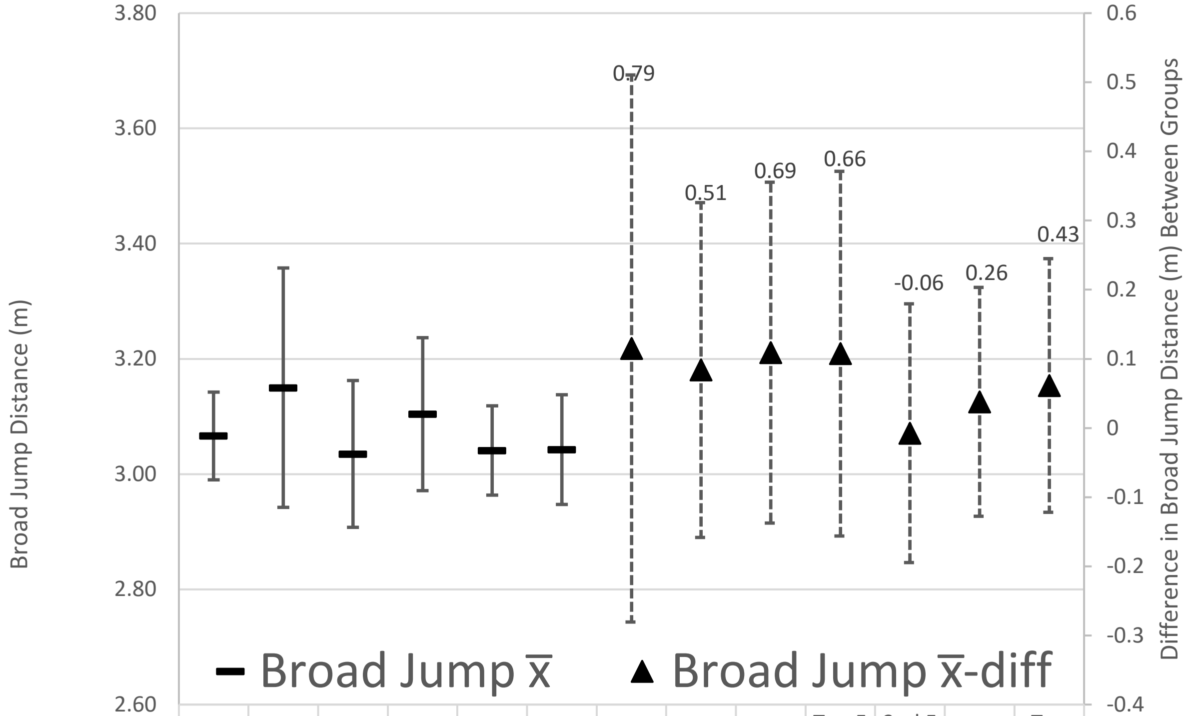
	All Athletes	Top 5	Second 5	Top 10	All But Top 5	All But Top 10	Top 5 vs. 2nd 5	Top 5 vs All	Top 5 vs. All But Top 5	Top 5 vs. All But Top 10	2nd 5 vs. All But Top 10	Top 10 vs. All	Top 10 vs. All But Top 10
60m x̄	6.83	6.77	6.69	6.73	6.85	6.89							
60m x̄-diff							0.08	-0.06	-0.082	-0.12	-0.20	-0.10	-0.16

Figure 4.29. NPC 2014, 60-m Sprint times for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.



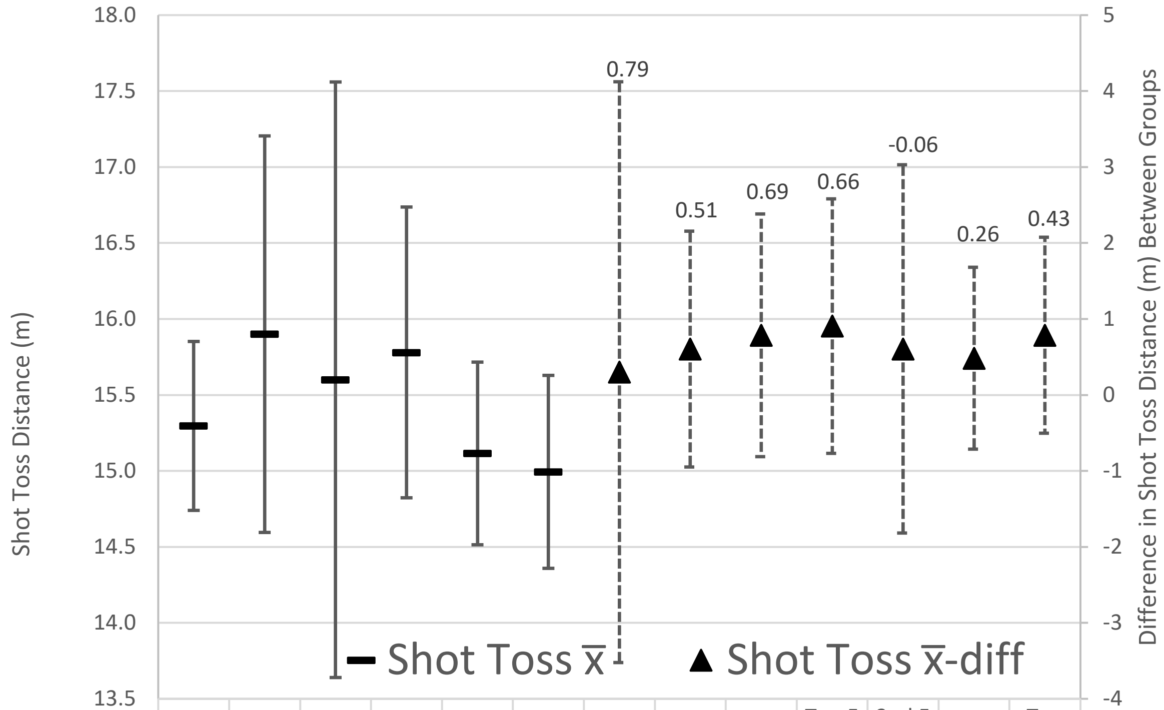
	All Athletes	Top 5	Second 5	Top 10	All But Top 5	All But Top 10	Top 5 vs. 2nd 5	Top 5 vs All	Top 5 vs. All But Top 5	Top 5 vs. All But Top 10	2nd 5 vs. All But Top 10	Top 10 vs. All	Top 10 vs. All But Top 10
30m Fly x̅	3.12	3.10	3.02	3.07	3.12	3.15							
30 m Fly x̅-diff							0.09	-0.02	-0.024	-0.05	-0.14	-0.05	-0.09

Figure 4.30. NPC 2014, 30-m Fly times for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.



	All Athletes	Top 5	Second 5	Top 10	All But Top 5	All But Top 10	Top 5 vs. 2nd 5	Top 5 vs All	Top 5 vs. All But Top 5	Top 5 vs. All But Top 10	2nd 5 vs. All But Top 10	Top 10 vs. All	Top 10 vs. All But Top 10
▬ Broad Jump x̅	3.07	3.15	3.04	3.10	3.04	3.04							
▲ Broad Jump x̅-diff							0.12	0.08	0.109	0.11	-0.01	0.04	0.06

Figure 4.31. NPC 2014, Broad Jump distances for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.



	All Athletes	Top 5	Second 5	Top 10	All But Top 5	All But Top 10	Top 5 vs. 2nd 5	Top 5 vs All	Top 5 vs. All But Top 5	Top 5 vs. All But Top 10	2nd 5 vs. All But Top 10	Top 10 vs. All	Top 10 vs. All But Top 10
Shot Toss x̅	15.30	15.90	15.60	15.78	15.12	14.99							
Shot Toss x̅-diff							0.30	0.60	0.785	0.91	0.61	0.48	0.79

Figure 4.32. NPC 2014, Underhand Shot Toss distances for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.

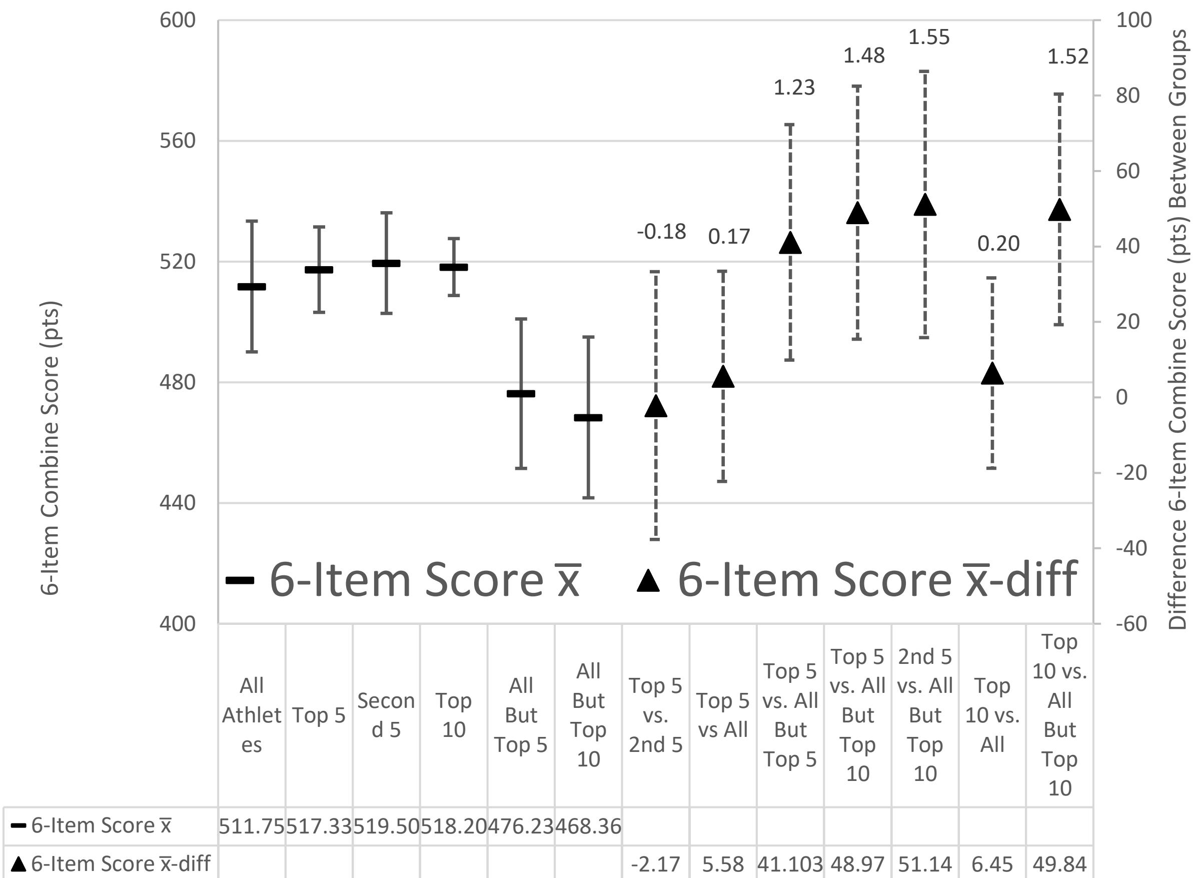
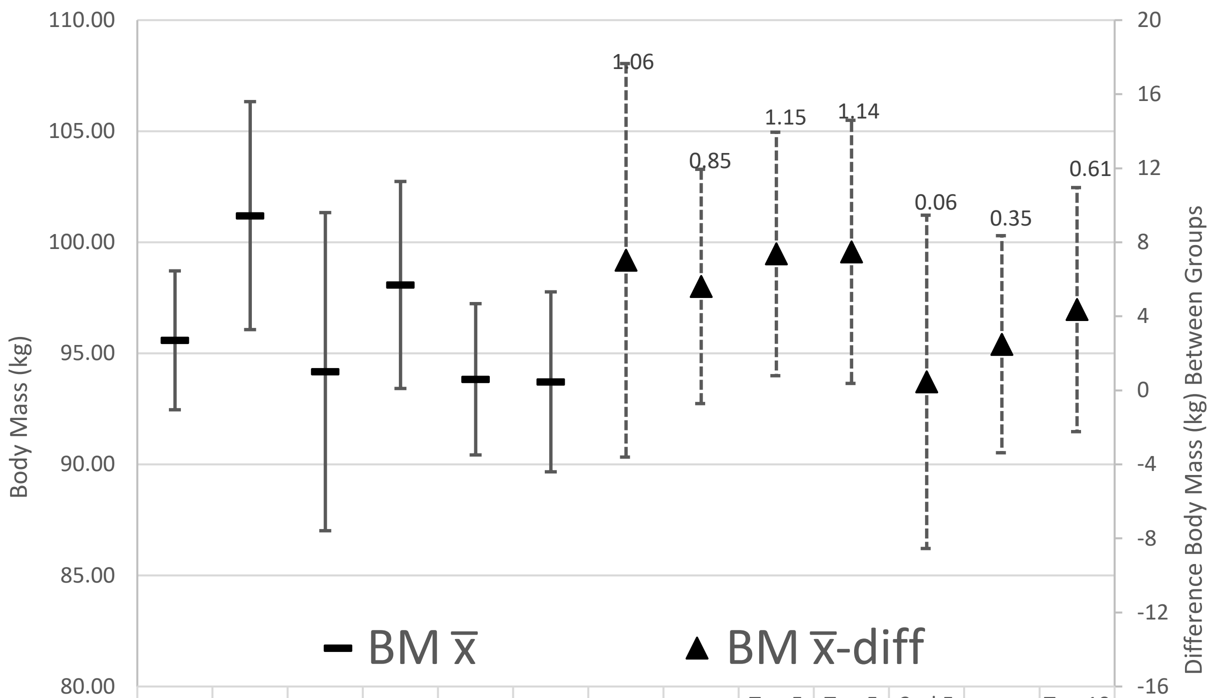
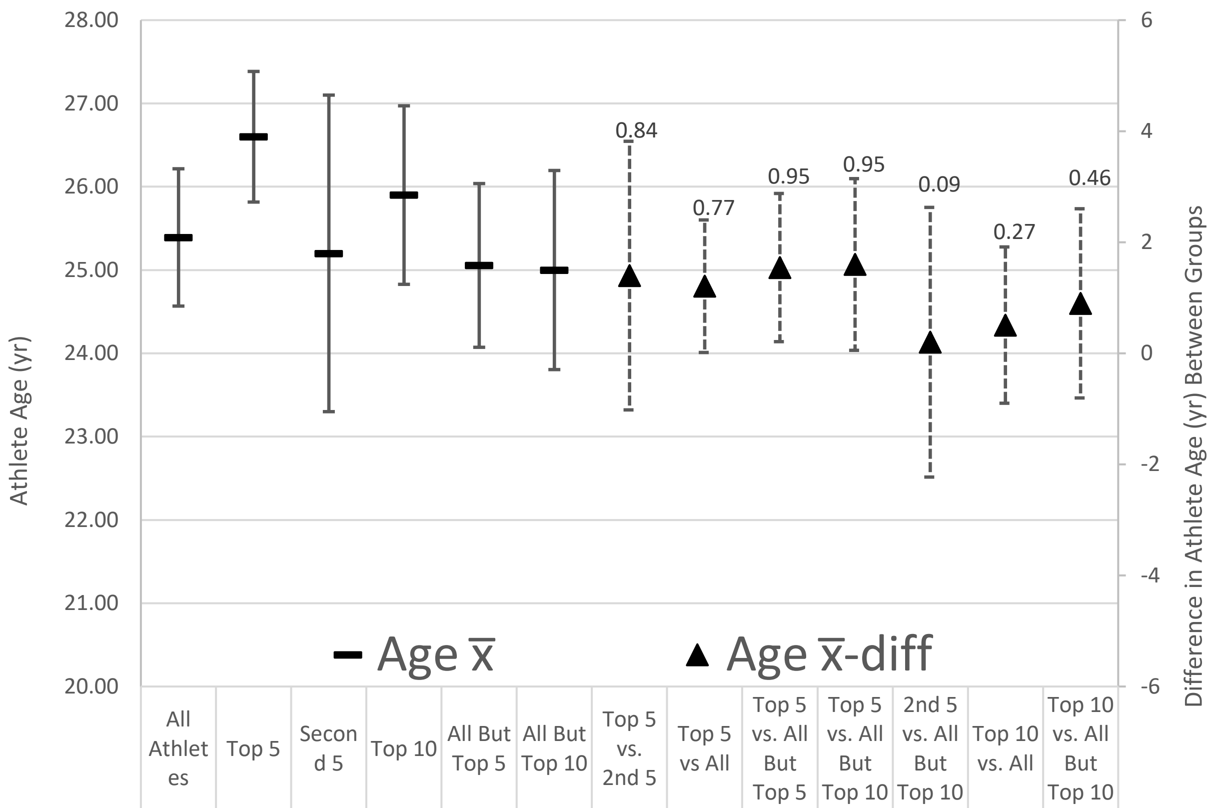


Figure 4.33. NPC 2014, 6-Item combine scores for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.



	All Athletes	Top 5	Second 5	Top 10	All But Top 5	All But Top 10	Top 5 vs. 2nd 5	Top 5 vs All	Top 5 vs. All But Top 5	Top 5 vs. All But Top 10	2nd 5 vs. All But Top 10	Top 10 vs. All	Top 10 vs. All But Top 10
BM x̄	95.59	101.20	94.18	98.08	93.83	93.72							
BM x̄-diff							7.03	5.61	7.37	7.48	0.46	2.49	4.36

Figure 4.34. NPC 2014, Body mass for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.

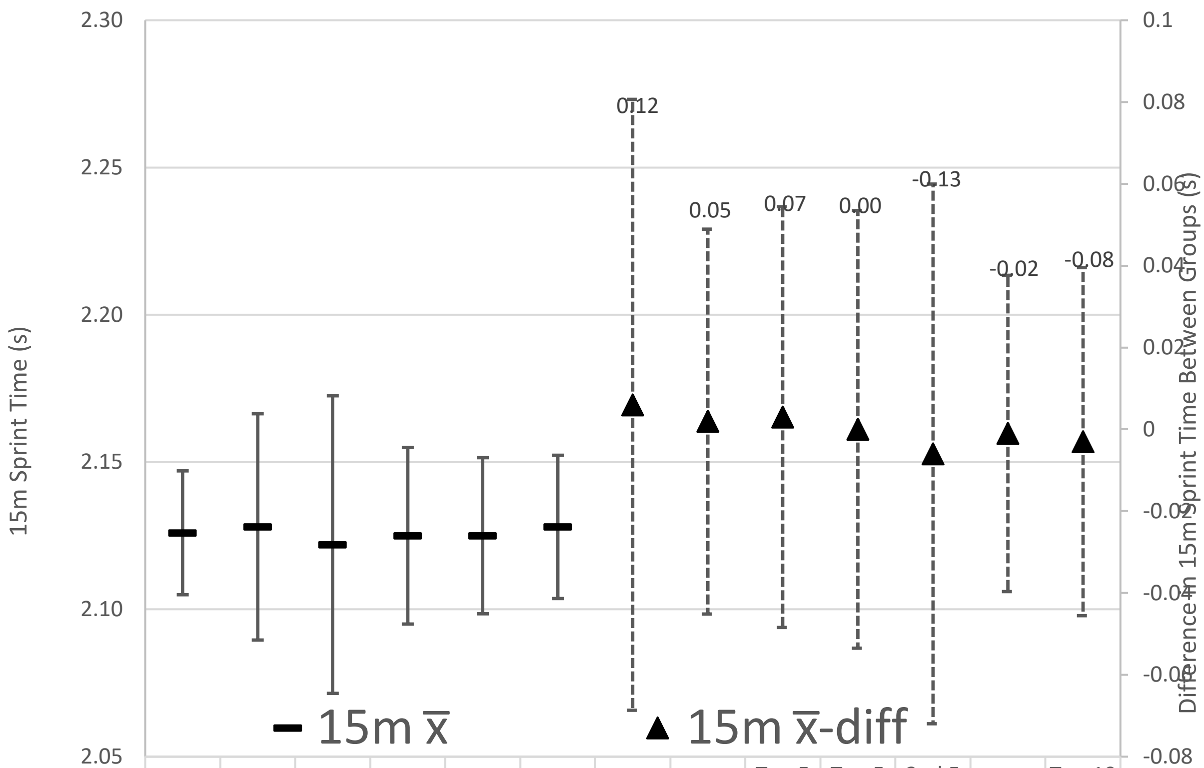


	All Athletes	Top 5	Second 5	Top 10	All But Top 5	All But Top 10	Top 5 vs. 2nd 5	Top 5 vs All	Top 5 vs. All But Top 5	Top 5 vs. All But Top 10	2nd 5 vs. All But Top 10	Top 10 vs. All	Top 10 vs. All But Top 10
Age x̄	25.39	26.60	25.20	25.90	25.06	25.00							
Age x̄-diff							1.40	1.21	1.544	1.60	0.20	0.51	0.90

Figure 4.35. NPC 2014, Athlete age for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.

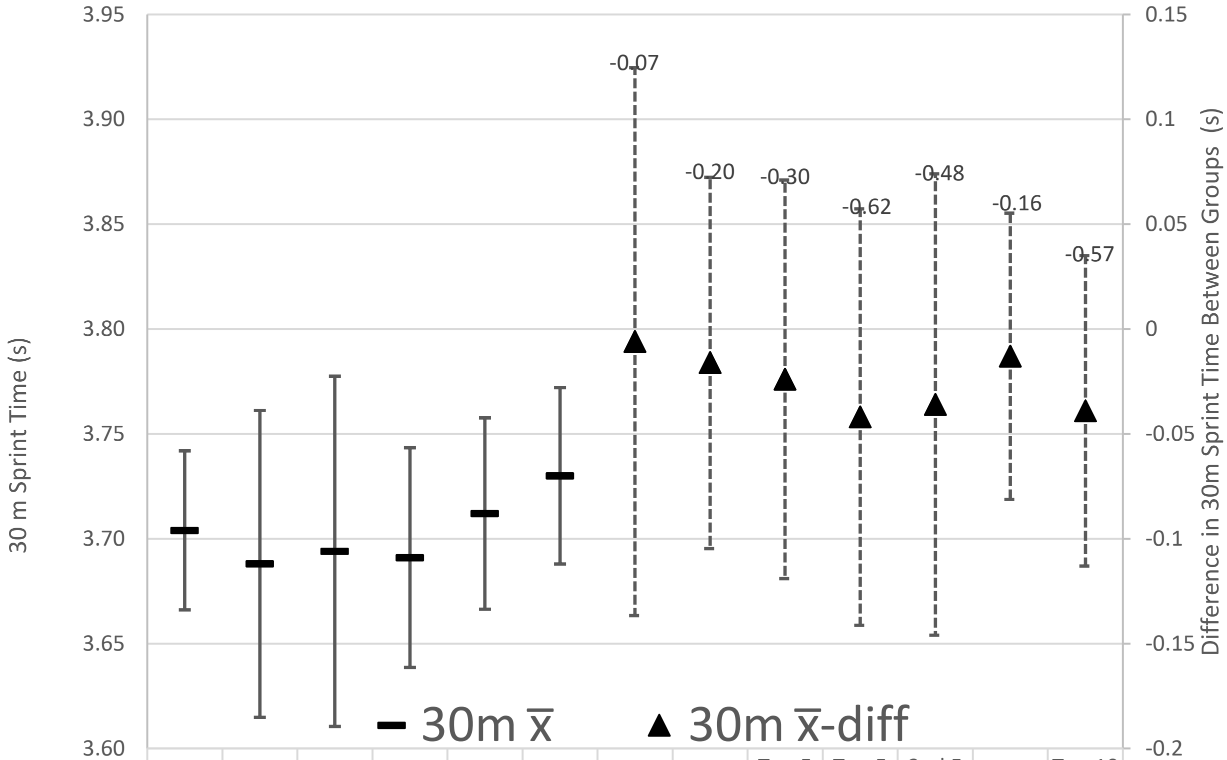
Appendix E

Ancillary Group Mean Comparisons for 2015 PPC



	All Athletes	Top 5	Second 5	Top 10	All But Top 5	All But Top 10	Top 5 vs. 2nd 5	Top 5 vs All	Top 5 vs. All But Top 5	Top 5 vs. All But Top 10	2nd 5 vs. All But Top 10	Top 10 vs. All	Top 10 vs. All But Top 10
15m x̄	2.13	2.13	2.12	2.13	2.13	2.13							
▲ 15m x̄-diff							0.01	0.00	0.003	0.00	-0.01	0.00	0.00

Figure 4.36. PPC 2015, 15-m Sprint times for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.



	All Athletes	Top 5	Second 5	Top 10	All But Top 5	All But Top 10	Top 5 vs. 2nd 5	Top 5 vs All	Top 5 vs. All But Top 5	Top 5 vs. All But Top 10	2nd 5 vs. All But Top 10	Top 10 vs. All	Top 10 vs. All But Top 10
30m x̄	3.70	3.69	3.69	3.69	3.71	3.73							
30m x̄-diff							-0.01	-0.02	-0.024	-0.04	-0.04	-0.01	-0.04

Figure 4.37. PPC 2015, 30-m Sprint times for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.

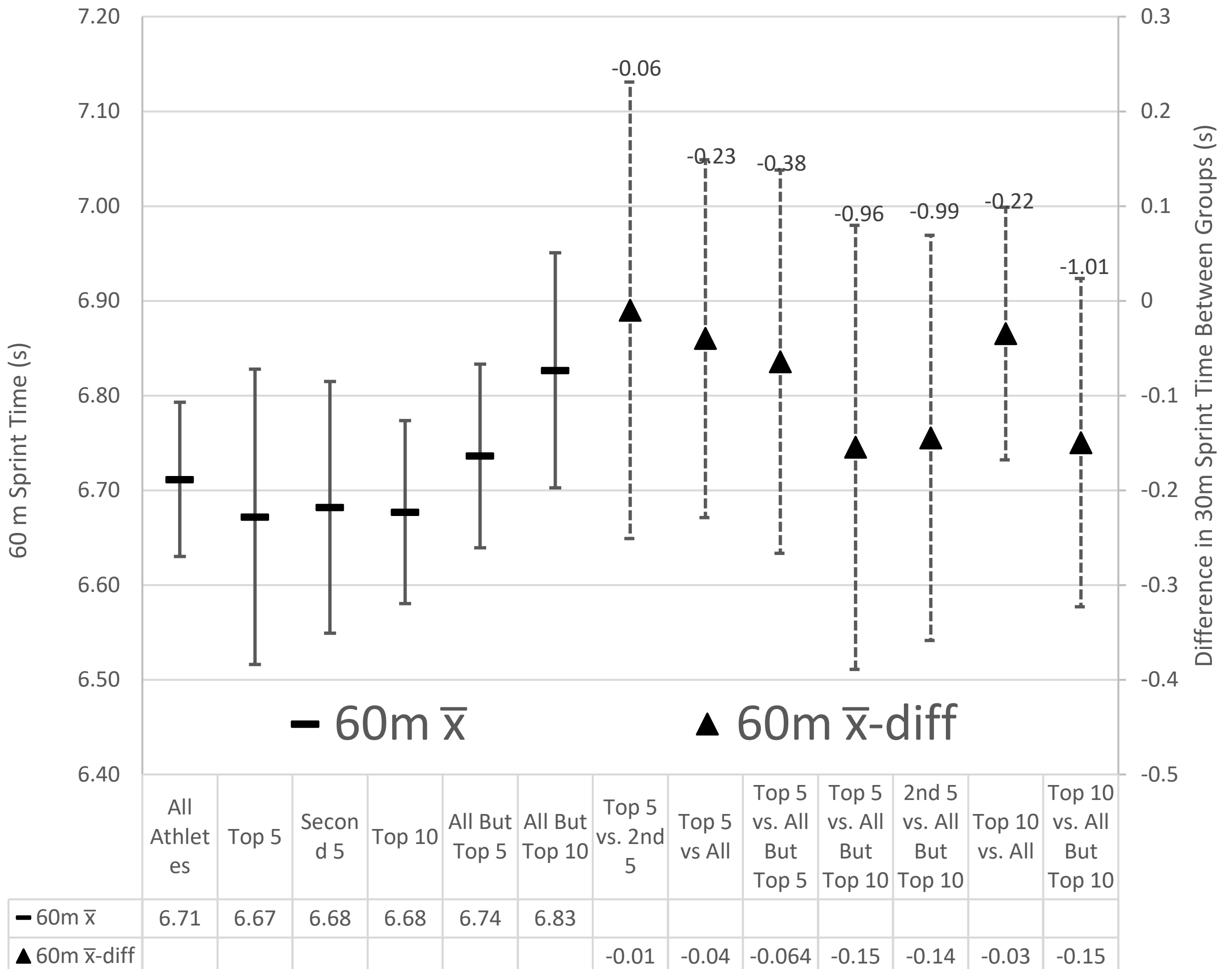
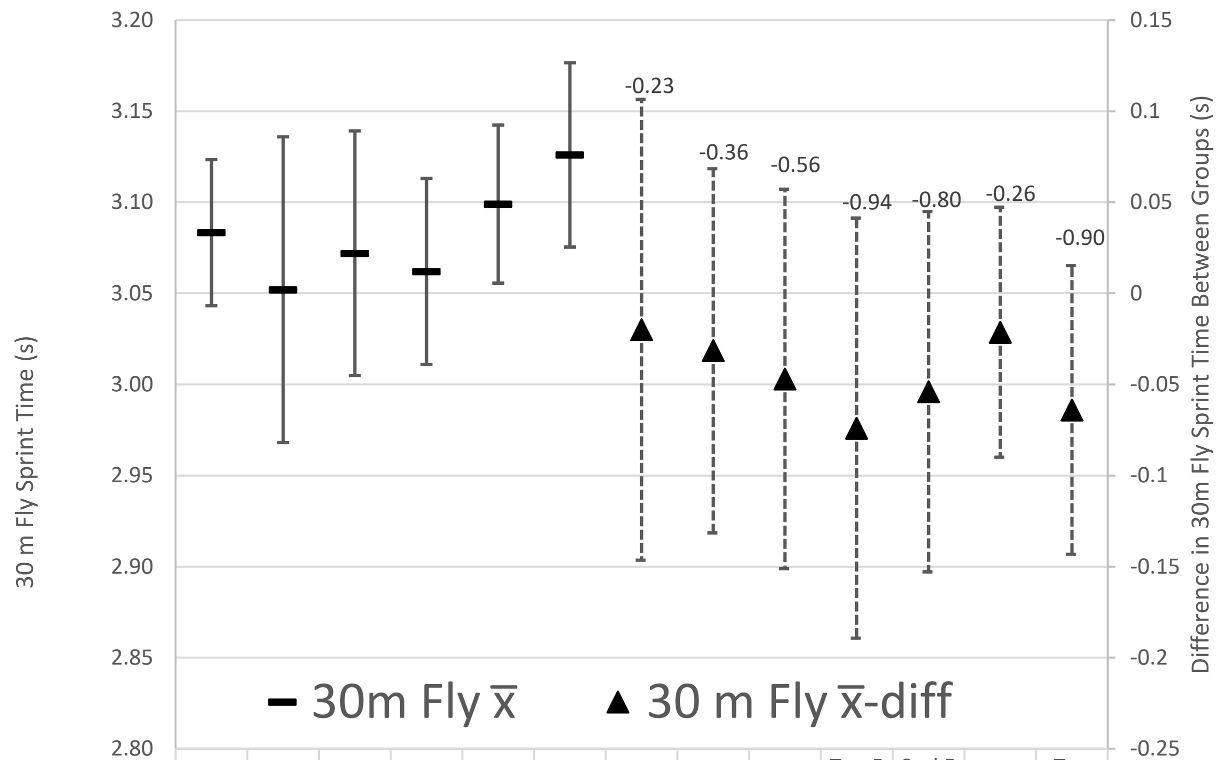
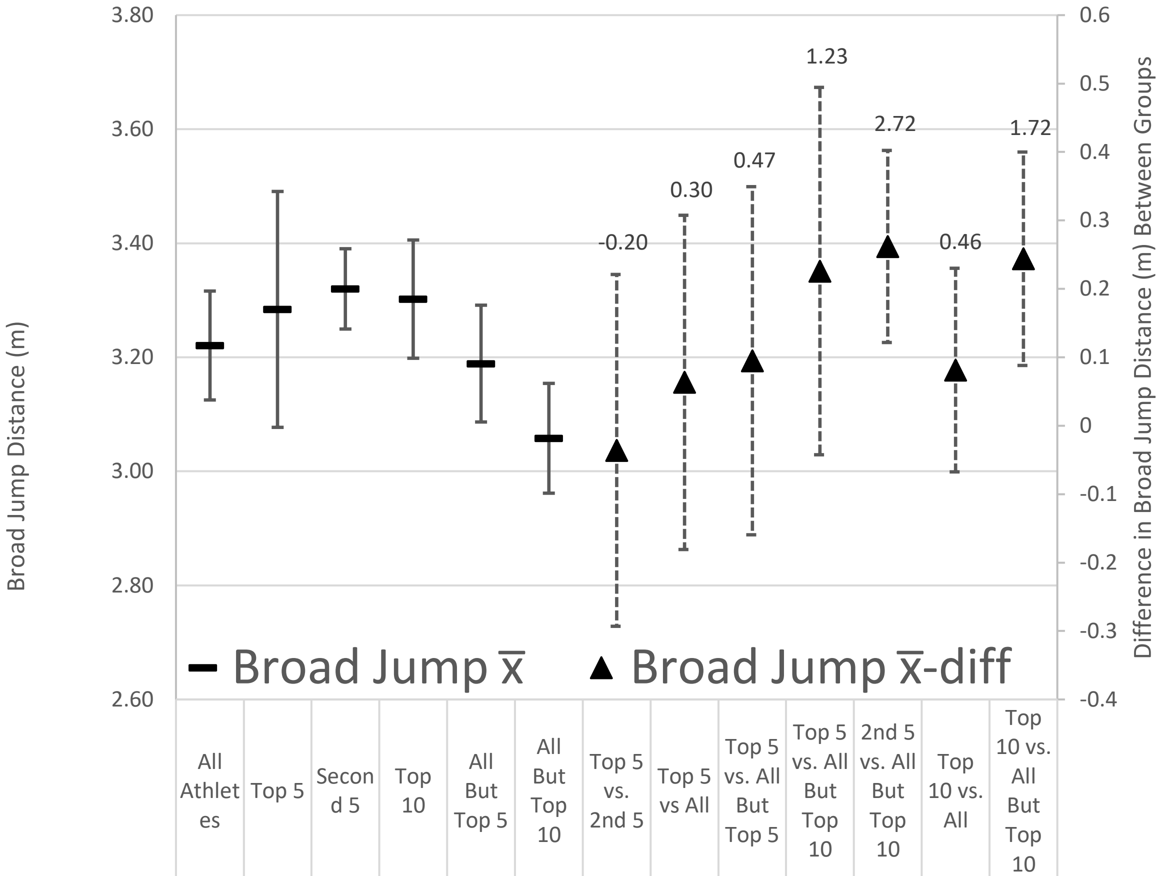


Figure 4.38. PPC 2015, 60-m Sprint times for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.



	All Athletes	Top 5	Second 5	Top 10	All But Top 5	All But Top 10	Top 5 vs. 2nd 5	Top 5 vs All	Top 5 vs. All But Top 5	Top 5 vs. All But Top 10	2nd 5 vs. All But Top 10	Top 10 vs. All	Top 10 vs. All But Top 10
30m Fly x̅	3.08	3.05	3.07	3.06	3.10	3.13							
30 m Fly x̅-diff							-0.02	-0.03	-0.047	-0.07	-0.05	-0.02	-0.06

Figure 4.39. PPC 2015, 30-m Fly times for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.



	All Athletes	Top 5	Second 5	Top 10	All But Top 5	All But Top 10	Top 5 vs. 2nd 5	Top 5 vs All	Top 5 vs. All But Top 5	Top 5 vs. All But Top 10	2nd 5 vs. All But Top 10	Top 10 vs. All	Top 10 vs. All But Top 10
Broad Jump x̄	3.22	3.28	3.32	3.30	3.19	3.06							
Broad Jump x̄-diff							-0.04	0.06	0.095	0.23	0.26	0.08	0.24

Figure 4.40. PPC 2015, Broad Jump distances for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.

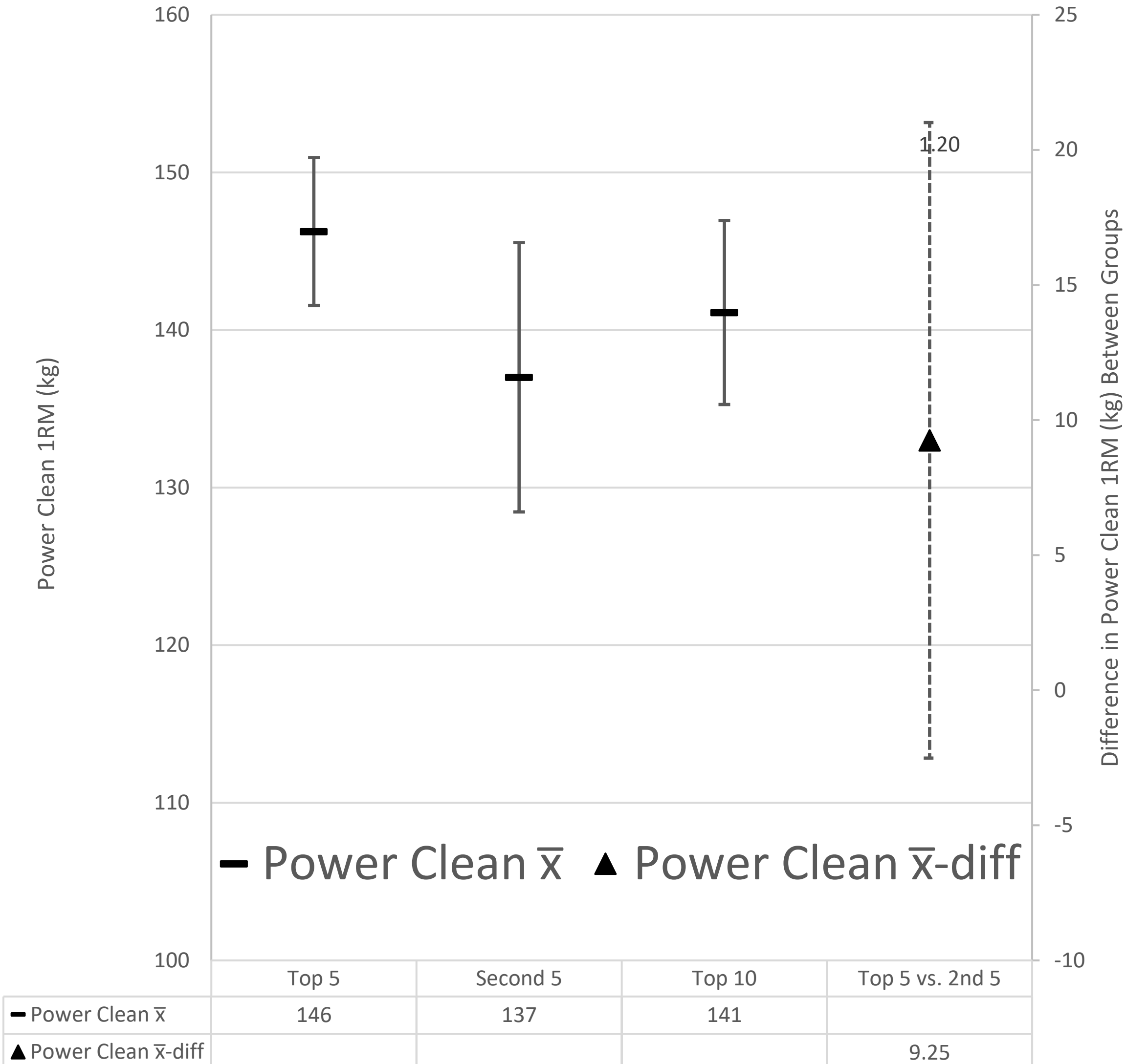


Figure 4.41. PPC 2015, 1RM Power Clean loads for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.

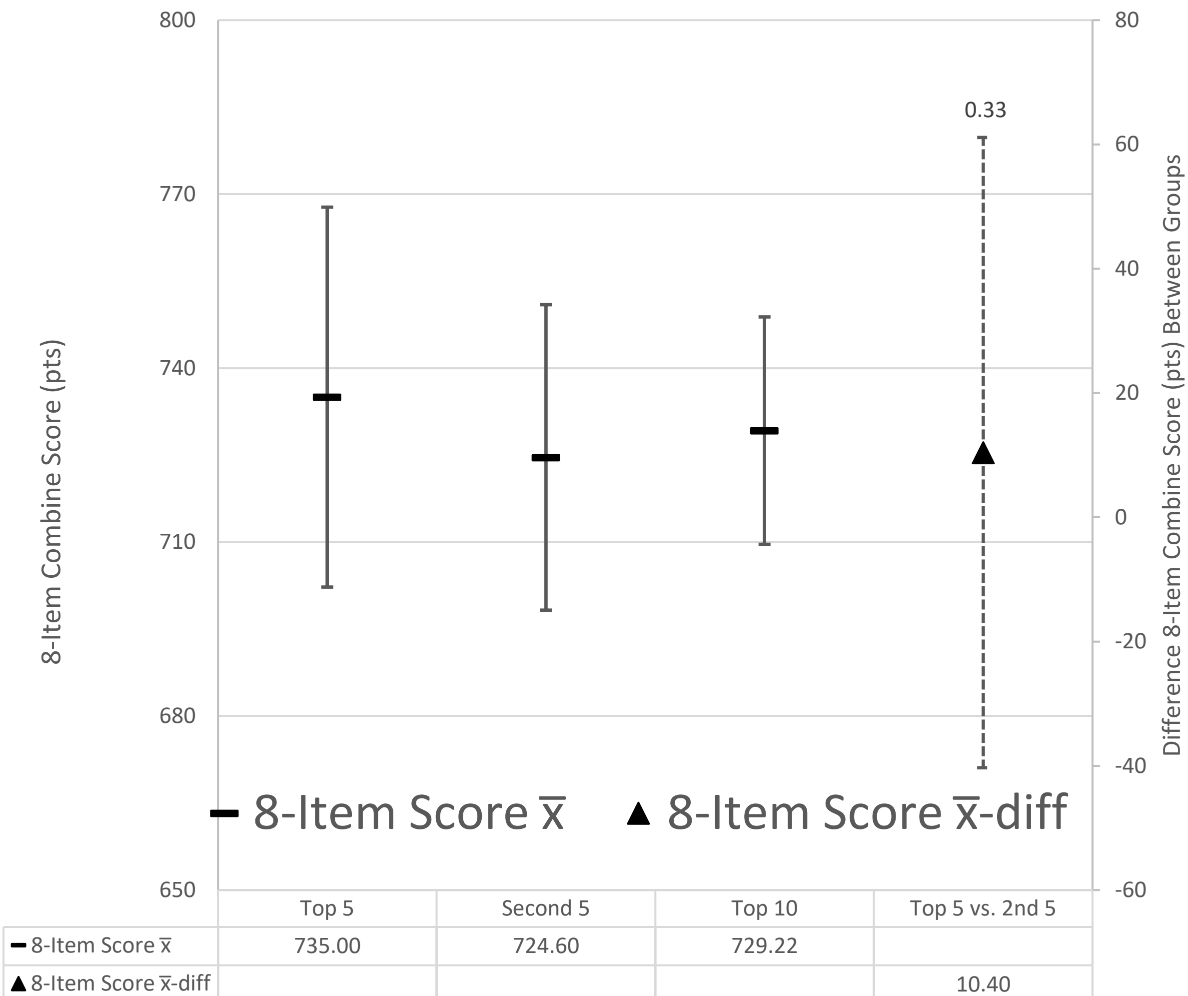


Figure 4.42. PPC 2015, 8-Item combine scores for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.

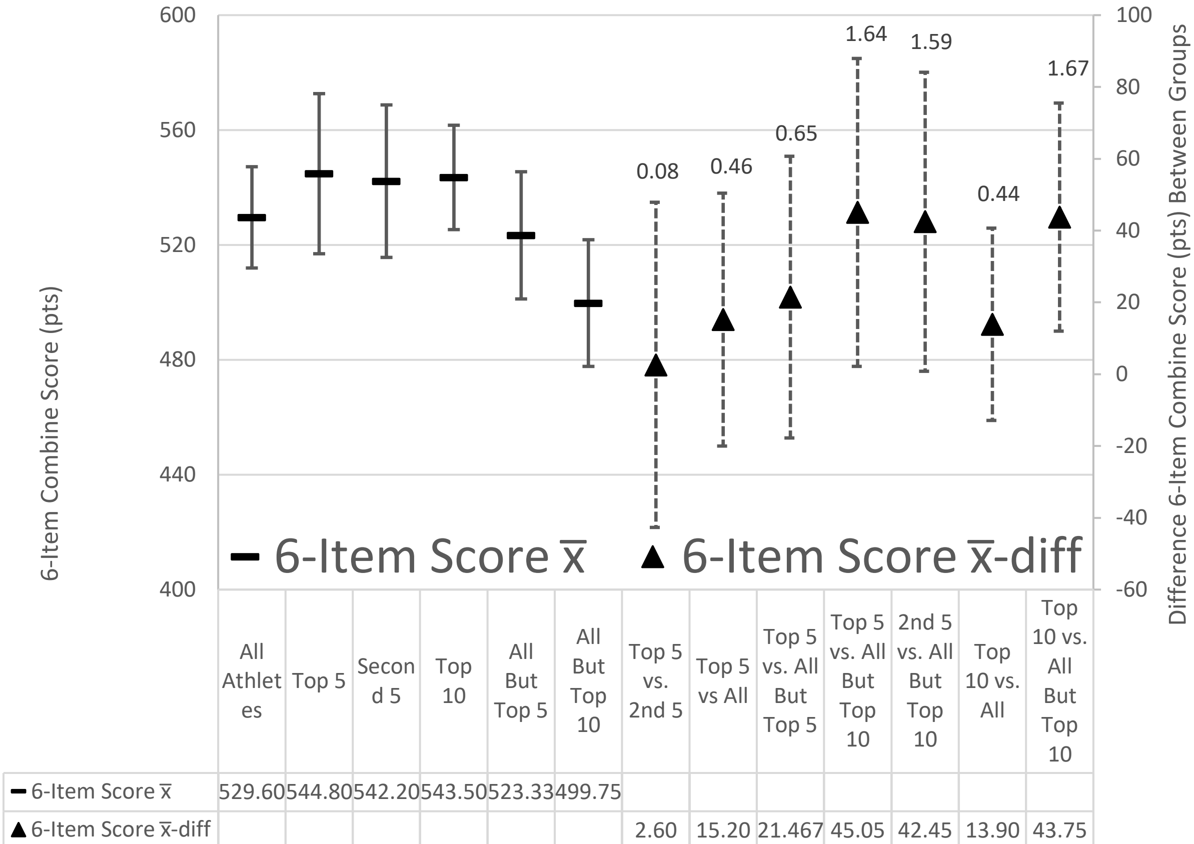


Figure 4.43. PPC 2015, 6-Item combine scores for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.

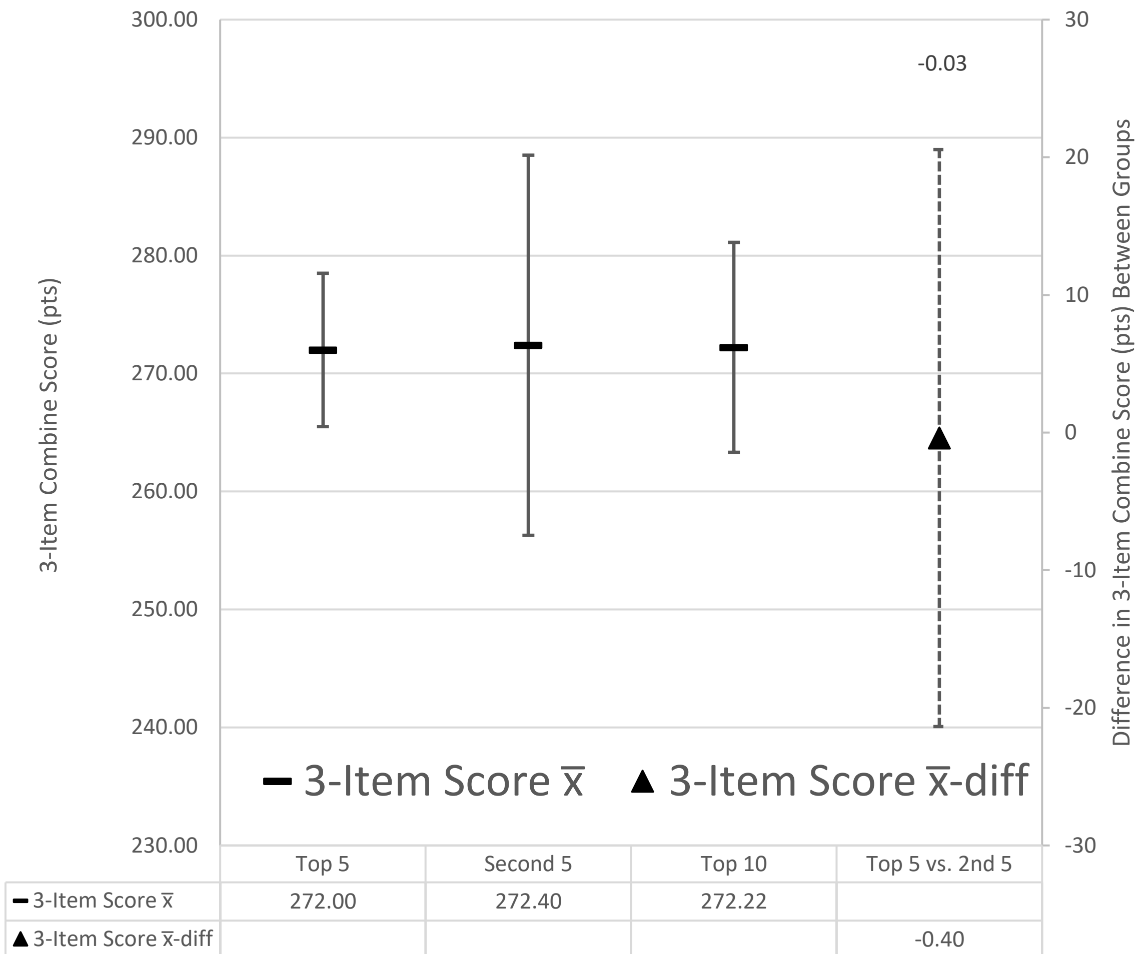
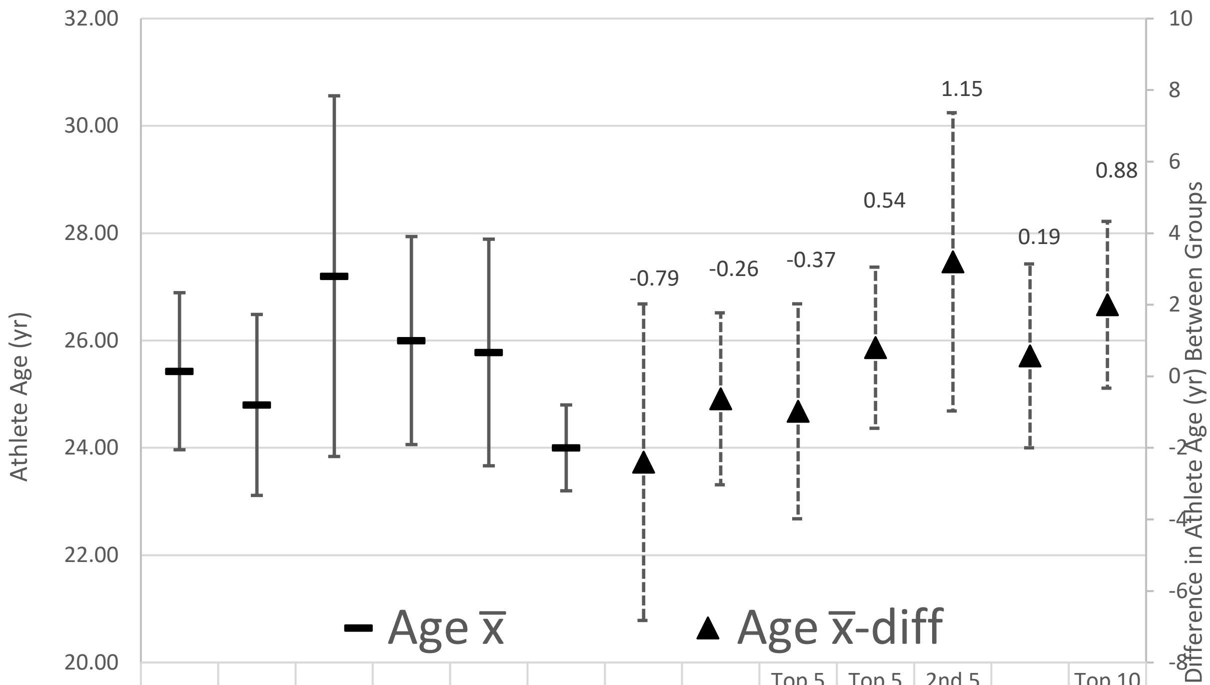


Figure 4.44. PPC 2015, 3-Item combine scores for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.

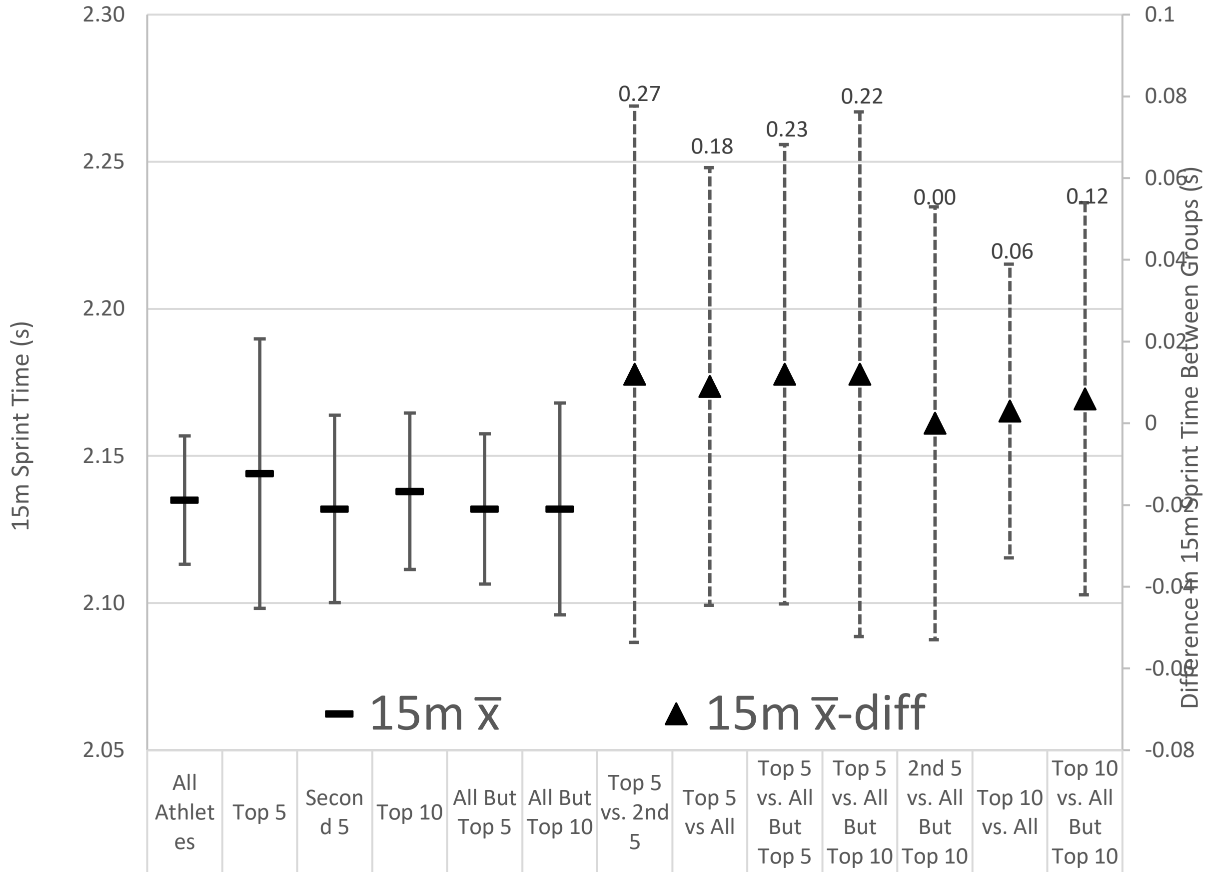


	All Athletes	Top 5	Second 5	Top 10	All But Top 5	All But Top 10	Top 5 vs. 2nd 5	Top 5 vs All	Top 5 vs. All But Top 5	Top 5 vs. All But Top 10	2nd 5 vs. All But Top 10	Top 10 vs. All	Top 10 vs. All But Top 10
▬ Age x̄	25.43	24.80	27.20	26.00	25.78	24.00							
▲ Age x̄-diff							-2.40	-0.63	-0.978	0.80	3.20	0.57	2.00

Figure 4.45. PPC 2015, Athete age for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.

Appendix F

Ancillary Group Mean Comparisons for 2015 NPC



	All Athletes	Top 5	Second 5	Top 10	All But Top 5	All But Top 10	Top 5 vs. 2nd 5	Top 5 vs All	Top 5 vs. All But Top 5	Top 5 vs. All But Top 10	2nd 5 vs. All But Top 10	Top 10 vs. All	Top 10 vs. All But Top 10
▬ 15m x̄	2.14	2.14	2.13	2.14	2.13	2.13							
▲ 15m x̄-diff							0.01	0.01	0.012	0.01	0.00	0.00	0.01

Figure 4.46. NPC 2015, 15-m Sprint times for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.

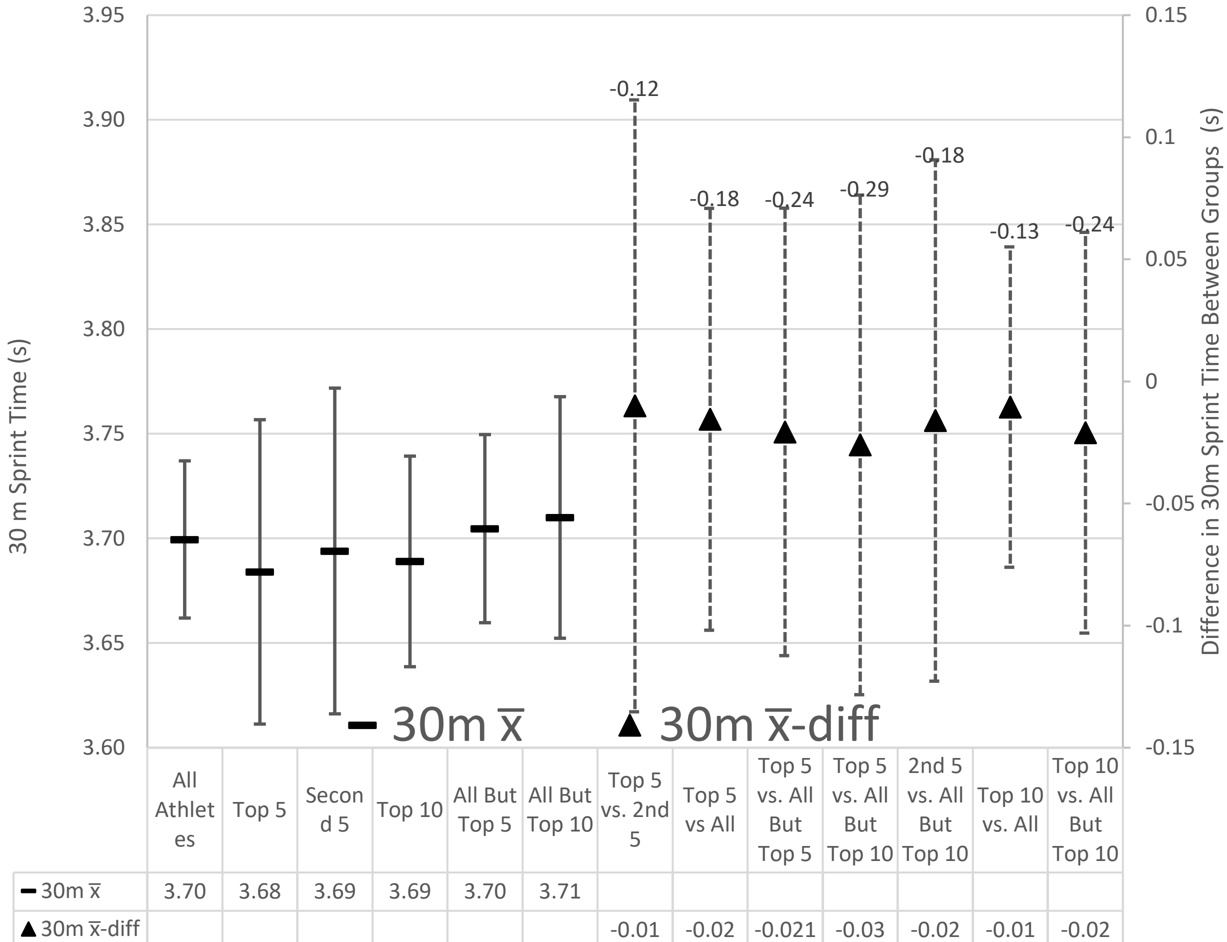
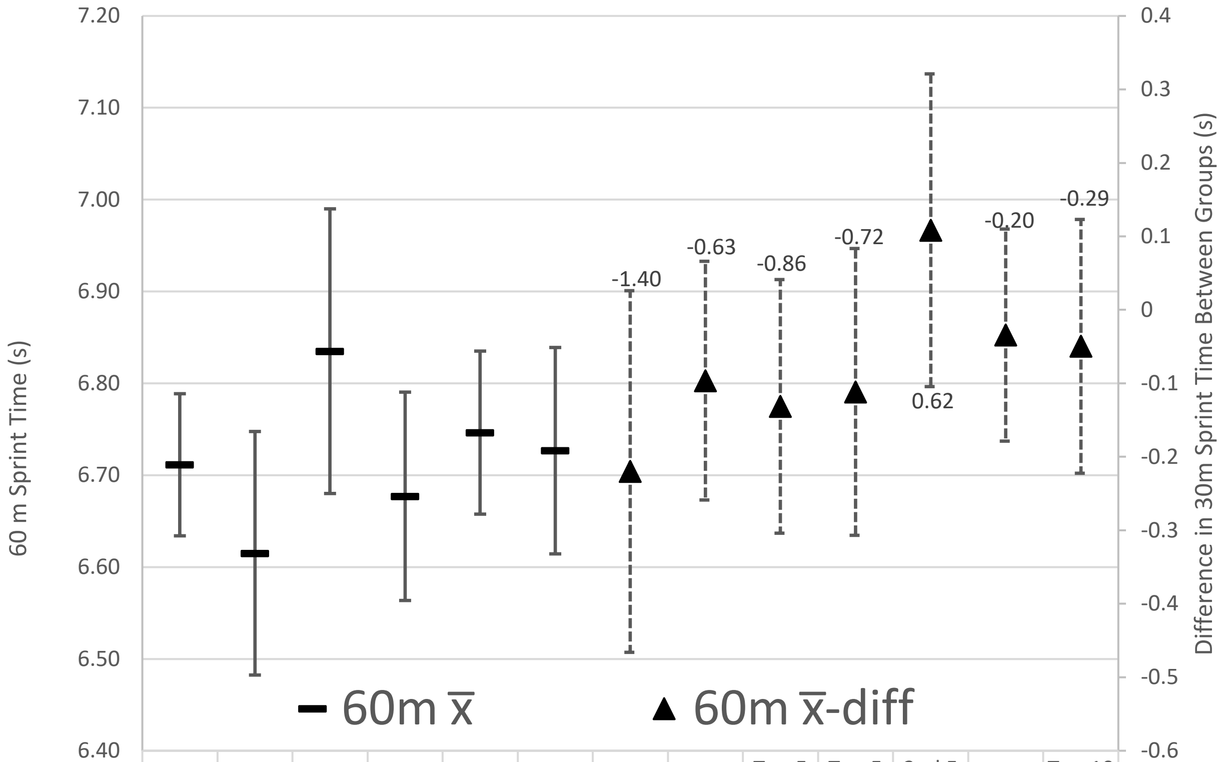
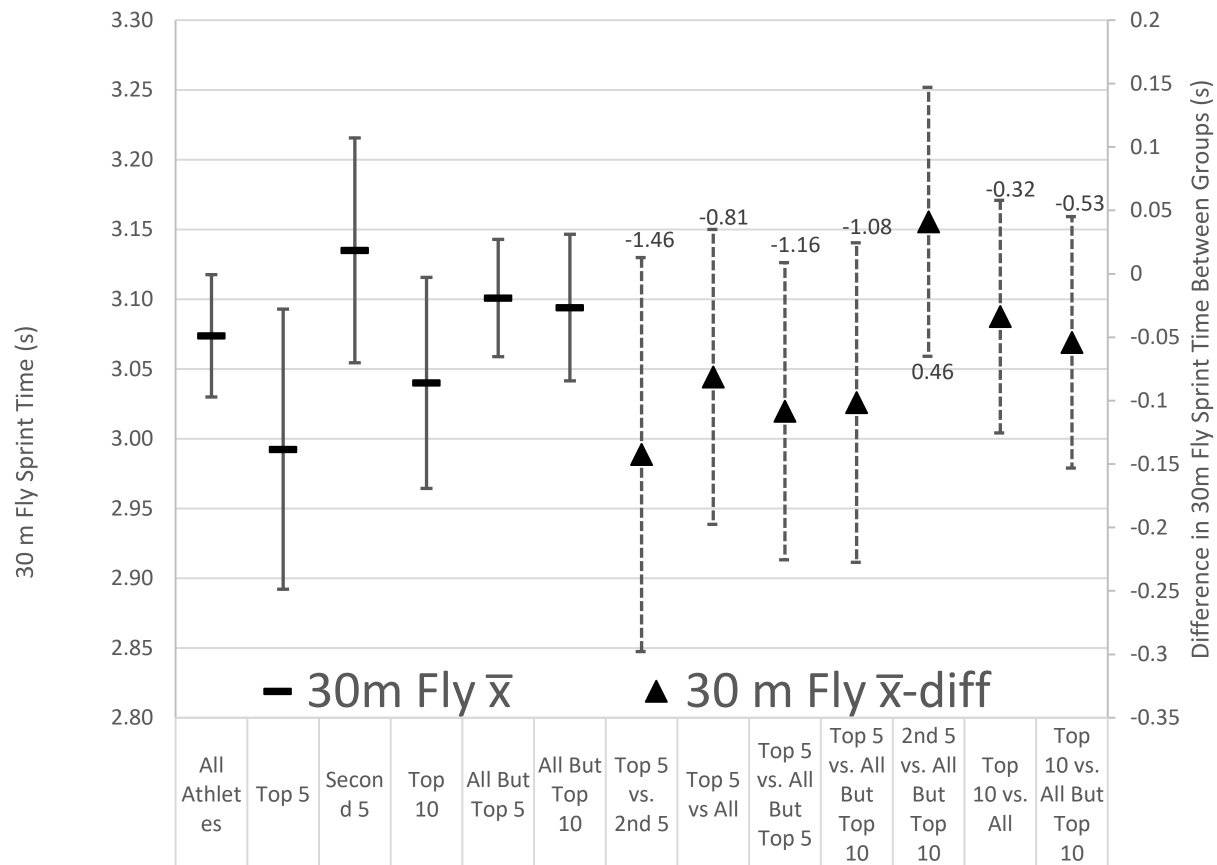


Figure 4.47. NPC 2015, 30-m Sprint times for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.



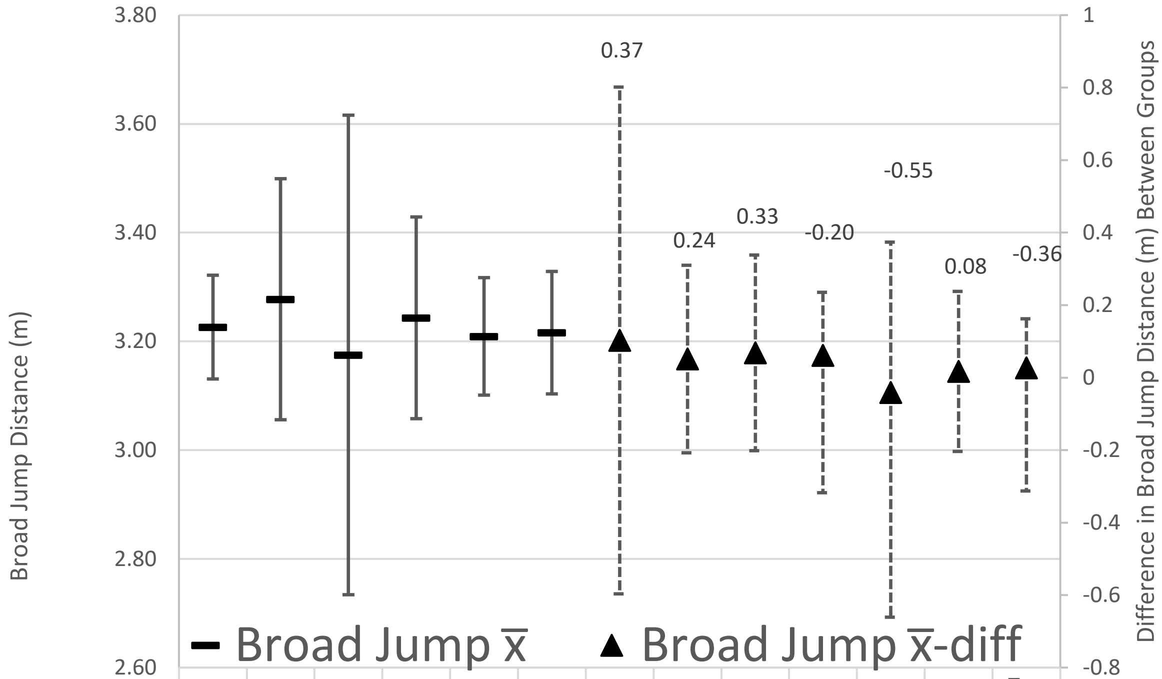
	All Athletes	Top 5	Second 5	Top 10	All But Top 5	All But Top 10	Top 5 vs. 2nd 5	Top 5 vs All	Top 5 vs. All But Top 5	Top 5 vs. All But Top 10	2nd 5 vs. All But Top 10	Top 10 vs. All	Top 10 vs. All But Top 10
60m x̄	6.71	6.62	6.84	6.68	6.75	6.73							
60m x̄-diff							-0.22	-0.10	-0.131	-0.11	0.11	-0.03	-0.05

Figure 4.48. NPC 2015, 60-m Sprint times for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.



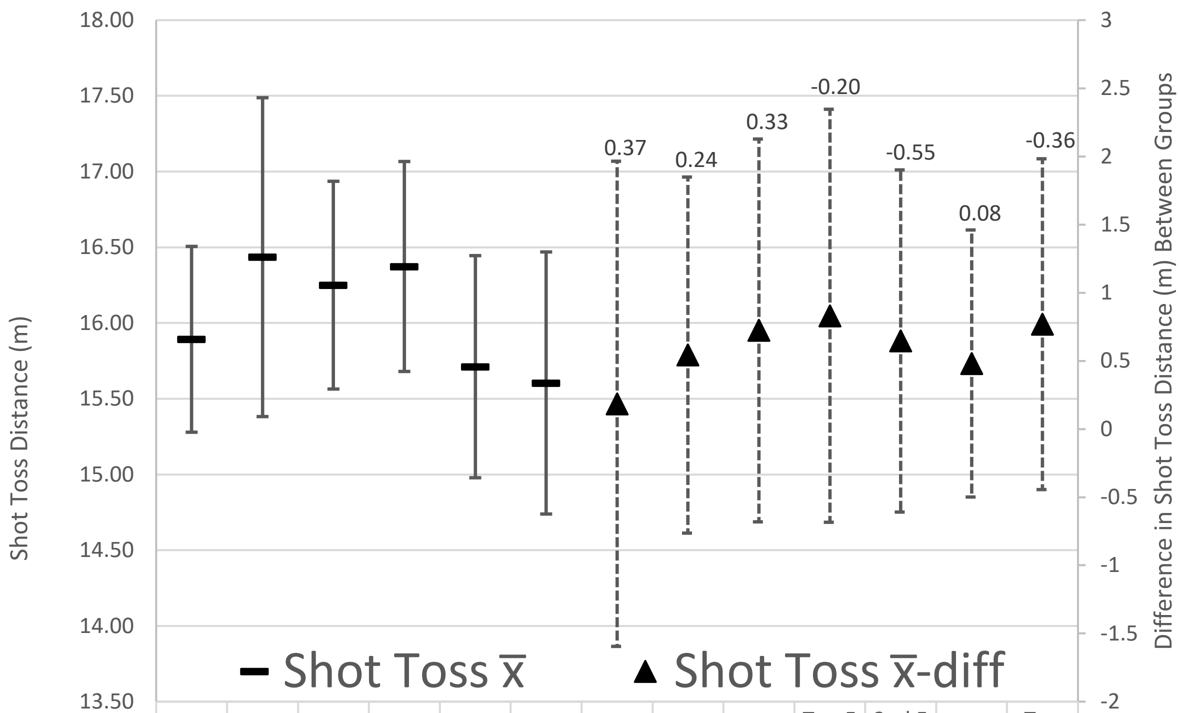
	All Athletes	Top 5	Second 5	Top 10	All But Top 5	All But Top 10	Top 5 vs. 2nd 5	Top 5 vs All	Top 5 vs. All But Top 5	Top 5 vs. All But Top 10	2nd 5 vs. All But Top 10	Top 10 vs. All	Top 10 vs. All But Top 10
30m Fly x̄	3.07	2.99	3.14	3.04	3.10	3.09							
30 m Fly x̄-diff							-0.14	-0.08	-0.108	-0.10	0.04	-0.03	-0.05

Figure 4.49. NPC 2015, 30-m Fly times for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.



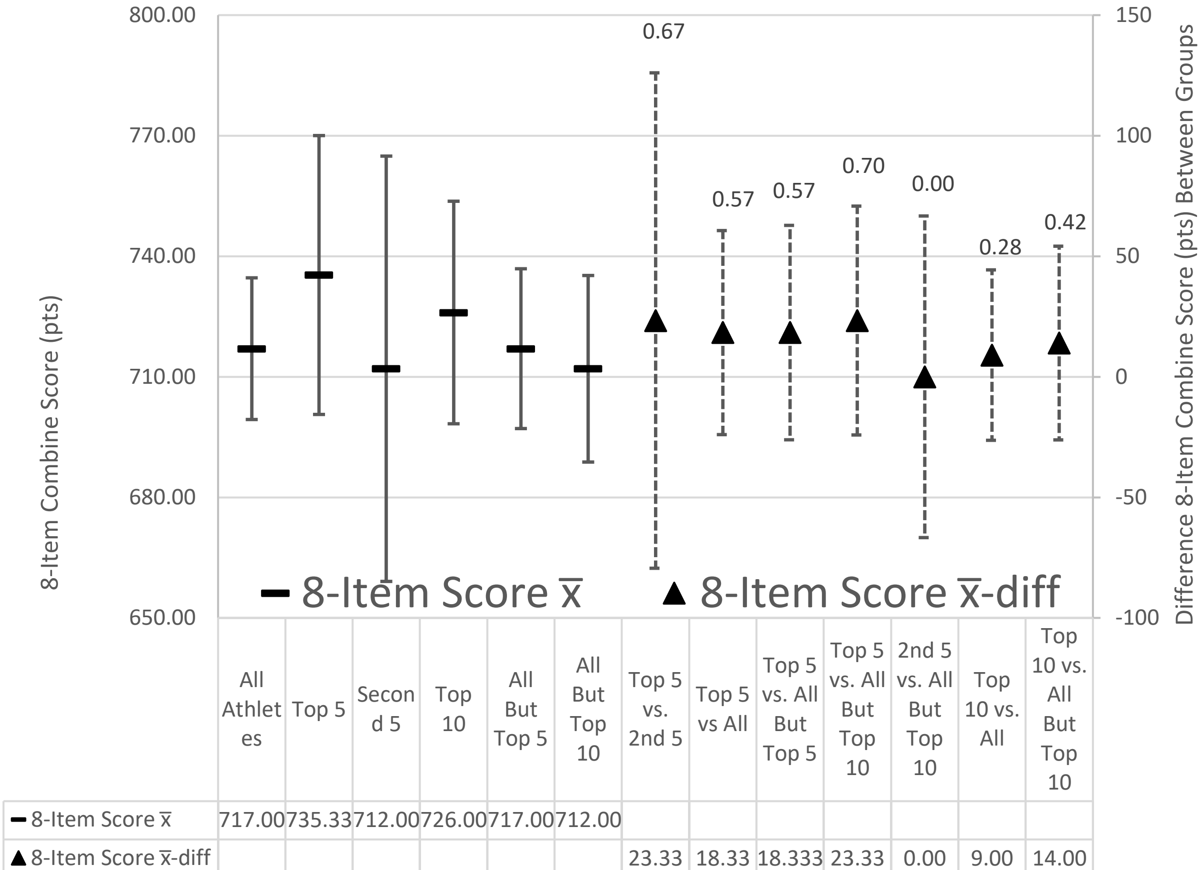
	All Athletes	Top 5	Second 5	Top 10	All But Top 5	All But Top 10	Top 5 vs. 2nd 5	Top 5 vs All	Top 5 vs. All But Top 5	Top 5 vs. All But Top 10	2nd 5 vs. All But Top 10	Top 10 vs. All	Top 10 vs. All But Top 10
Broad Jump x̄	3.23	3.28	3.18	3.24	3.21	3.22							
Broad Jump x̄-diff							0.10	0.05	0.068	0.06	-0.04	0.02	0.03

Figure 4.50. NPC 2015, Broad Jump distances for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.



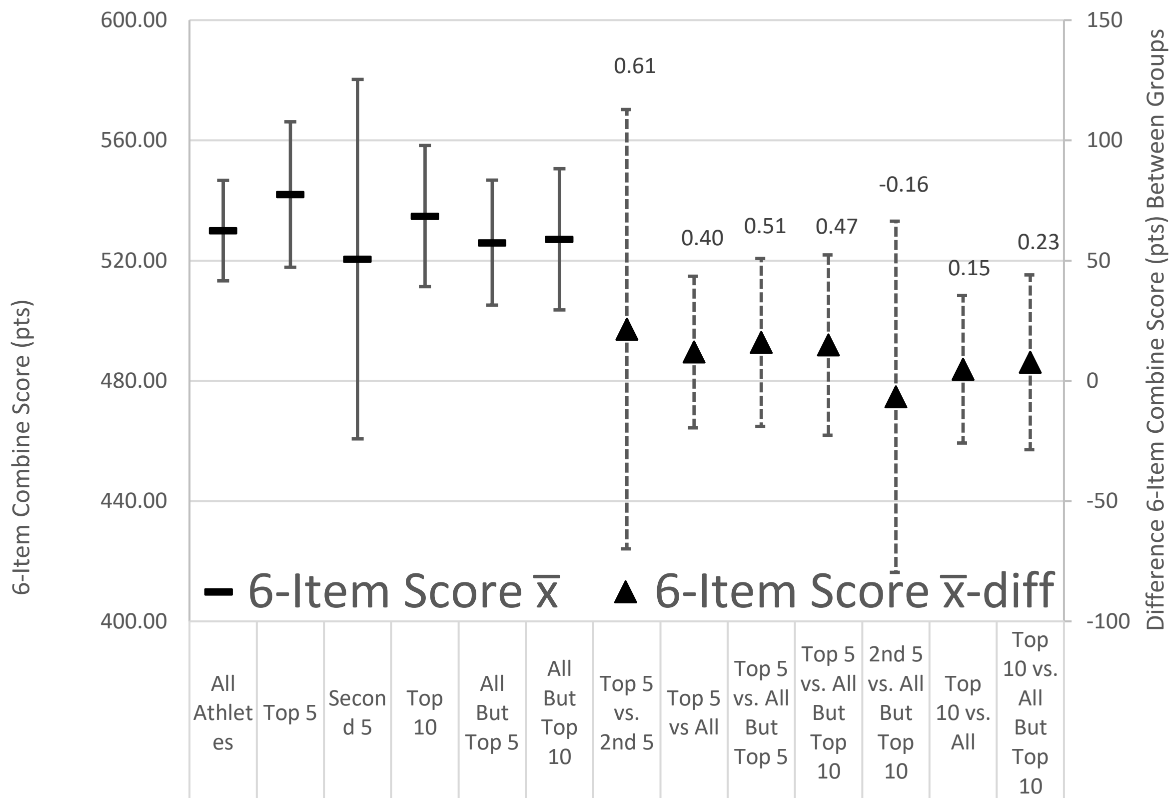
	All Athletes	Top 5	Second 5	Top 10	All But Top 5	All But Top 10	Top 5 vs. 2nd 5	Top 5 vs All	Top 5 vs. All But Top 5	Top 5 vs. All But Top 10	2nd 5 vs. All But Top 10	Top 10 vs. All	Top 10 vs. All But Top 10
Shot Toss x̅	15.89	16.44	16.25	16.37	15.71	15.60							
Shot Toss x̅-diff							0.19	0.54	0.723	0.83	0.65	0.48	0.77

Figure 4.51. NPC 2015, Underhand Shot Toss distances for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.



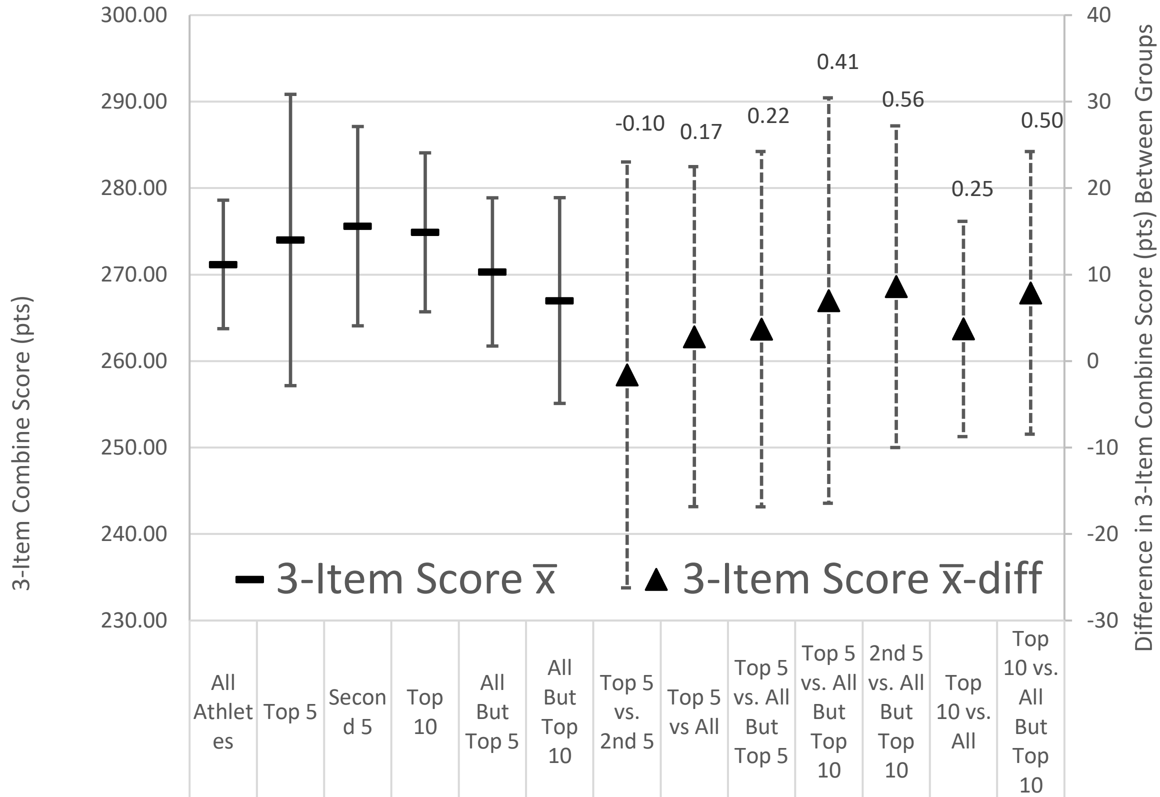
	All Athletes	Top 5	Second 5	Top 10	All But Top 5	All But Top 10	Top 5 vs. 2nd 5	Top 5 vs All	Top 5 vs. All But Top 5	Top 5 vs. All But Top 10	2nd 5 vs. All But Top 10	Top 10 vs. All	Top 10 vs. All But Top 10
8-Item Score x̅	717.00	735.33	712.00	726.00	717.00	712.00							
8-Item Score x̅-diff							23.33	18.33	18.333	23.33	0.00	9.00	14.00

Figure 4.52. NPC 2015, 8-Item Combine Scores for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.



	All Athletes	Top 5	Second 5	Top 10	All But Top 5	All But Top 10	Top 5 vs. 2nd 5	Top 5 vs All	Top 5 vs. All But Top 5	Top 5 vs. All But Top 10	2nd 5 vs. All But Top 10	Top 10 vs. All	Top 10 vs. All But Top 10
6-Item Score x̅	530.00	542.00	520.50	534.83	526.00	527.10							
6-Item Score x̅-diff							21.50	12.00	16.000	14.90	-6.60	4.83	7.73

Figure 4.53. NPC 2015, 6-Item Combine Scores for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.



	All Athletes	Top 5	Second 5	Top 10	All But Top 5	All But Top 10	Top 5 vs. 2nd 5	Top 5 vs All	Top 5 vs. All But Top 5	Top 5 vs. All But Top 10	2nd 5 vs. All But Top 10	Top 10 vs. All	Top 10 vs. All But Top 10
▬ 3-Item Score x̄	271.18	274.00	275.60	274.89	270.31	267.00							
▲ 3-Item Score x̄-diff							-1.60	2.82	3.692	7.00	8.60	3.71	7.89

Figure 4.54. NPC 2015, 3-Item Combine Scores for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.

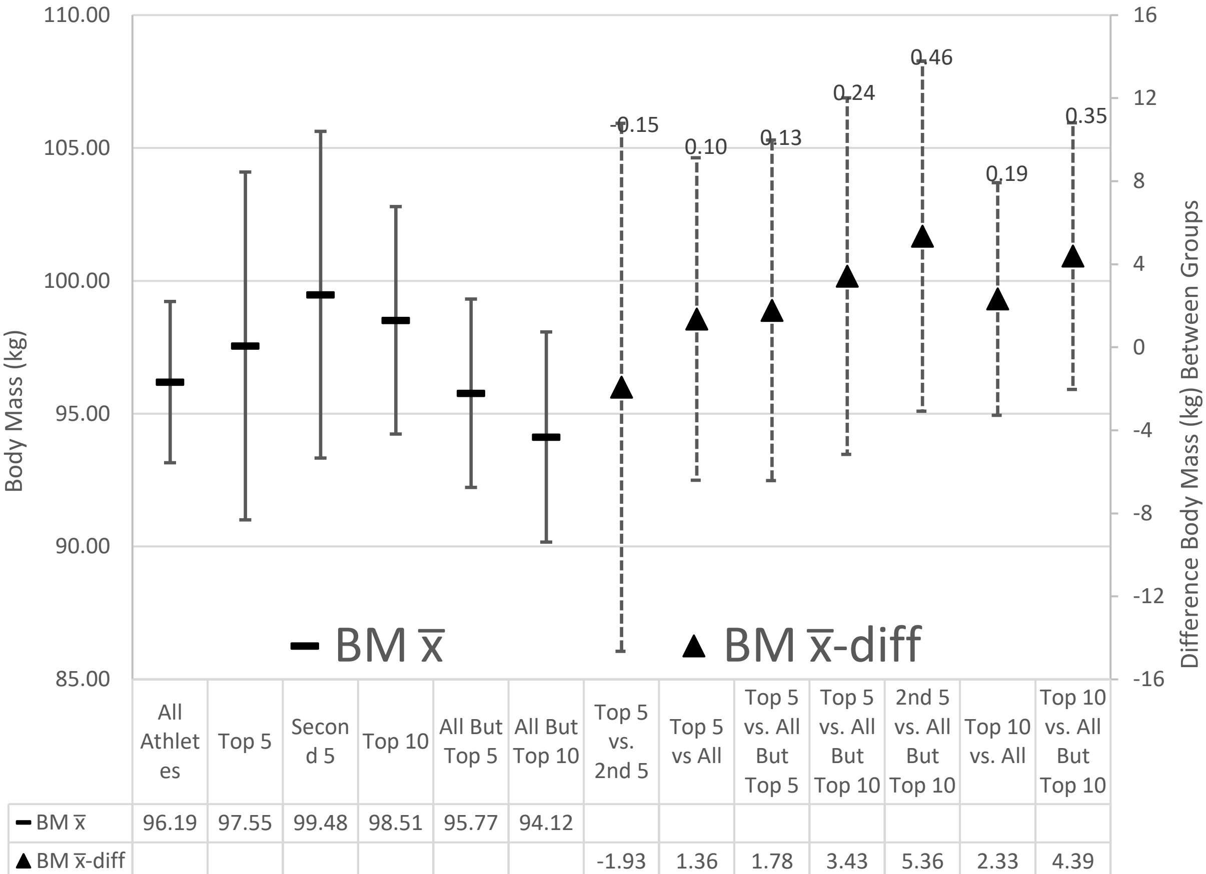
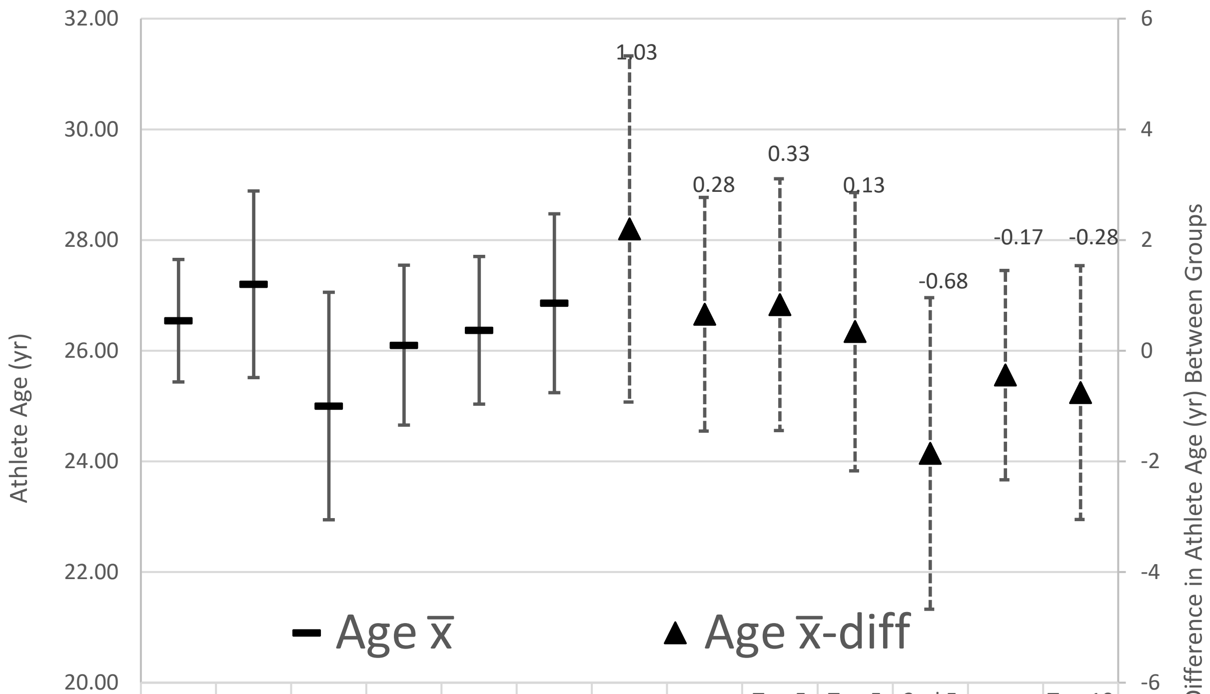


Figure 4.55. NPC 2015, Body Mass for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.



	All Athletes	Top 5	Second 5	Top 10	All But Top 5	All But Top 10	Top 5 vs. 2nd 5	Top 5 vs All	Top 5 vs. All But Top 5	Top 5 vs. All But Top 10	2nd 5 vs. All But Top 10	Top 10 vs. All	Top 10 vs. All But Top 10
Age x̄	26.54	27.20	25.00	26.10	26.37	26.86							
Age x̄-diff							2.20	0.66	0.832	0.34	-1.86	-0.44	-0.76

Figure 4.56. NPC 2015, Athlete Age for all groups and differences between groups. Dash symbol is group mean +/- 95% confidence intervals. Triangle symbol is group mean differences for each comparison listed below, +/- 95% mean difference confidence intervals. Effect sizes are displayed numerically, directly above mean difference positive confidence interval lines within the graph.

Appendix G

Ancillary Regressions Relating Combine Variables to Total Push Time in 2014 PPC

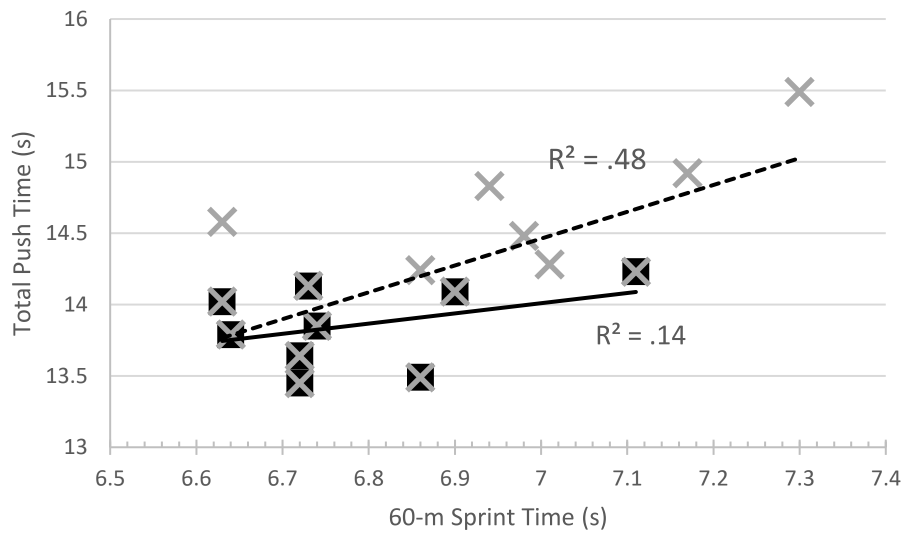


Figure 4.57. PPC 2014, 60-m Sprint times plotted against total push times presented with linear regressions for TOP10 and ALL, and their respective R^2 values on the graph. Gray "X" and dashed trendline represents ALL athletes. Solid black box and solid black trendline represents TOP10 athletes.

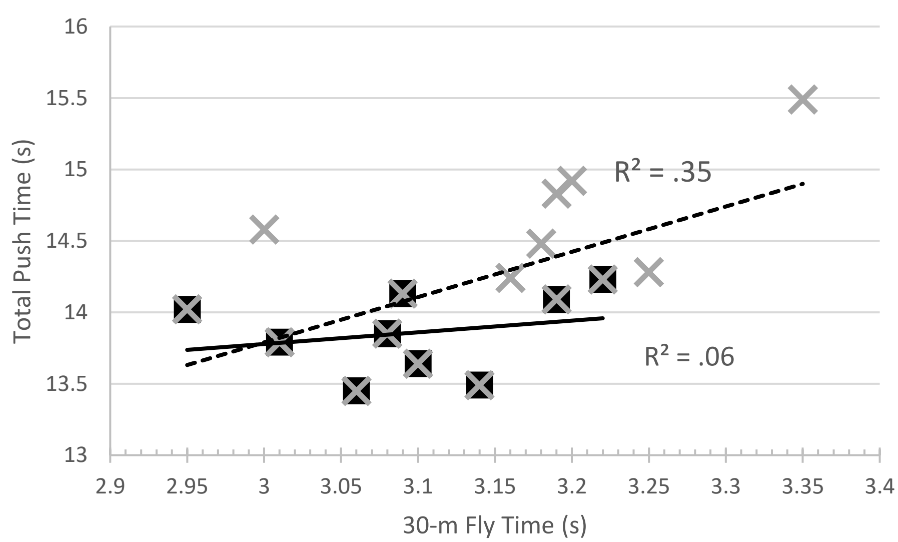


Figure 4.58. PPC 2014, 30-m Fly times plotted against total push times presented with linear regressions for TOP10 and ALL, and their respective R^2 values on the graph. Gray "X" and dashed trendline represents ALL athletes. Solid black box and solid black trendline represents TOP10 athletes.

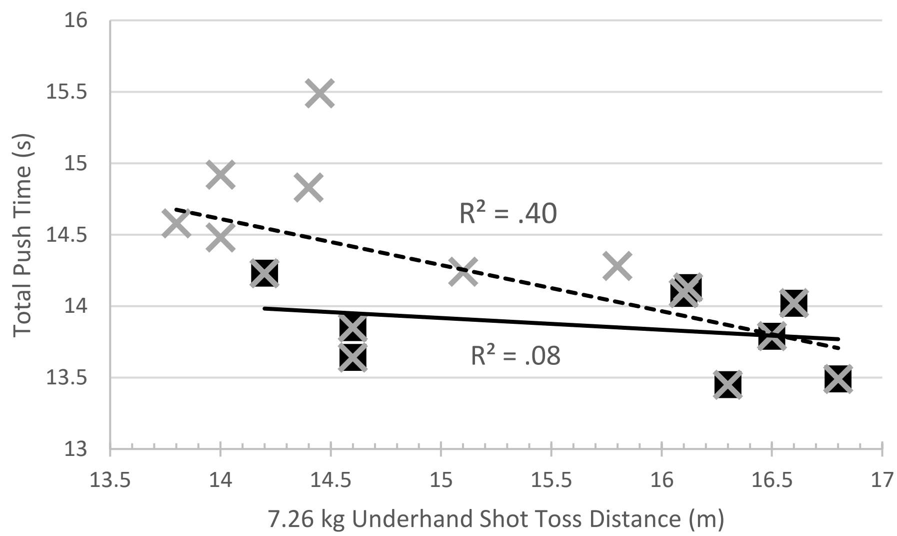


Figure 4.59. PPC 2014, UST distance plotted against total push times presented with linear regressions for TOP10 and ALL, and their respective R^2 values on the graph. Gray "X" and dashed trendline represents ALL athletes. Solid black box and solid black trendline represents TOP10 athletes.

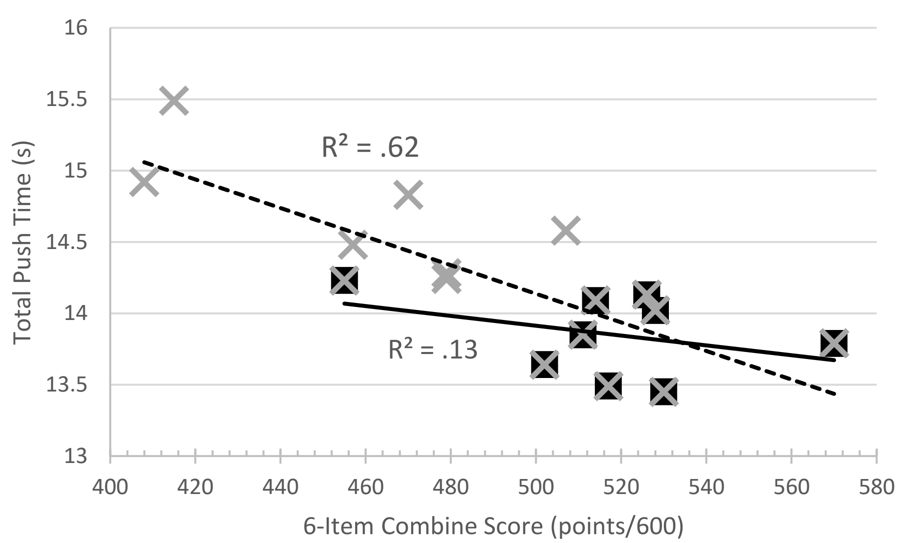


Figure 4.60. PPC 2014, 6-Item Combine scores plotted against total push times presented with linear regressions for TOP10 and ALL, and their respective R^2 values on the graph. Gray "X" and dashed trendline represents ALL athletes. Solid black box and solid black trendline represents TOP10 athletes.

Appendix H

Ancillary Regressions Relating Combine Variables to Total Push Time in 2014 NPC

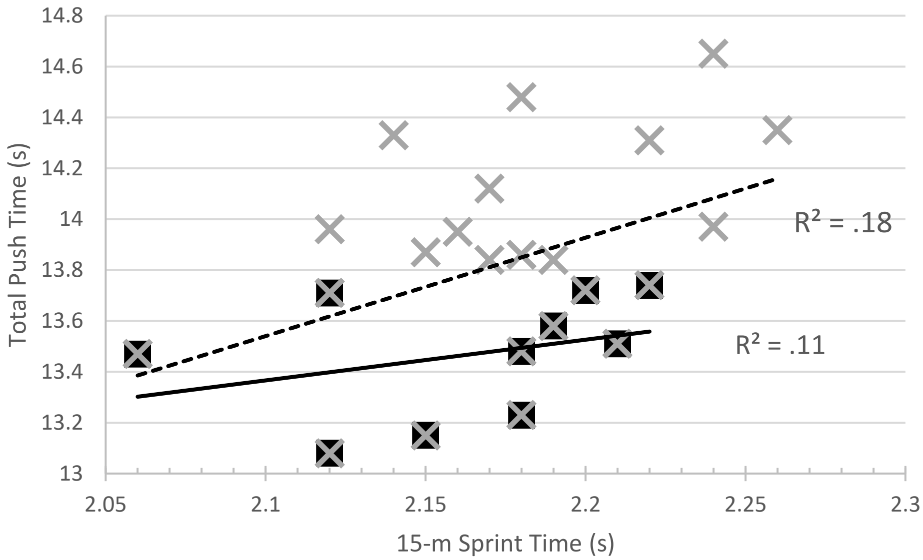


Figure 4.61. NPC 2014, 15-m Sprint times plotted against total push times presented with linear regressions for TOP10 and ALL, and their respective R^2 values on the graph. Gray "X" and dashed trendline represents ALL athletes. Solid black box and solid black trendline represents TOP10 athletes.

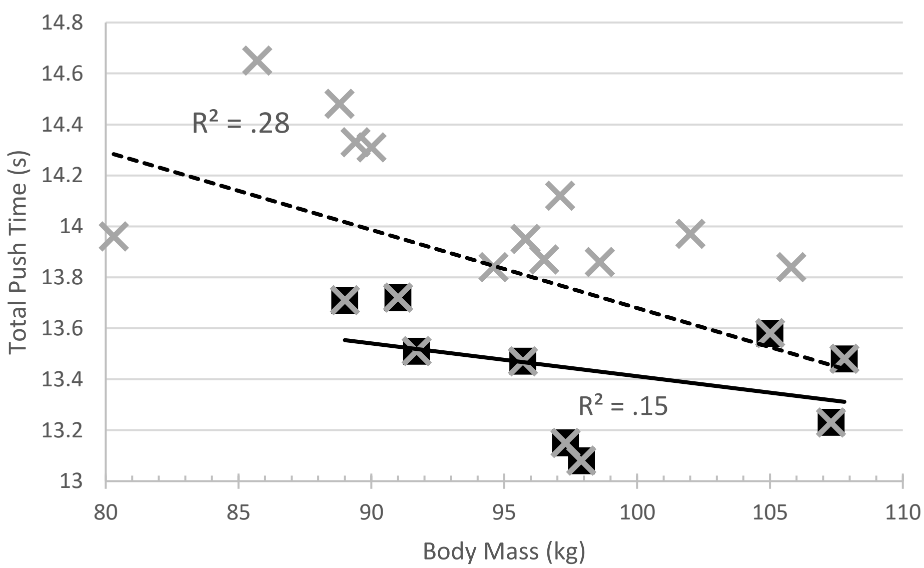


Figure 4.62. NPC 2014, Body mass plotted against total push times presented with linear regressions for TOP10 and ALL, and their respective R^2 values on the graph. Gray "X" and dashed trendline represents ALL athletes. Solid black box and solid black trendline represents TOP10 athletes.

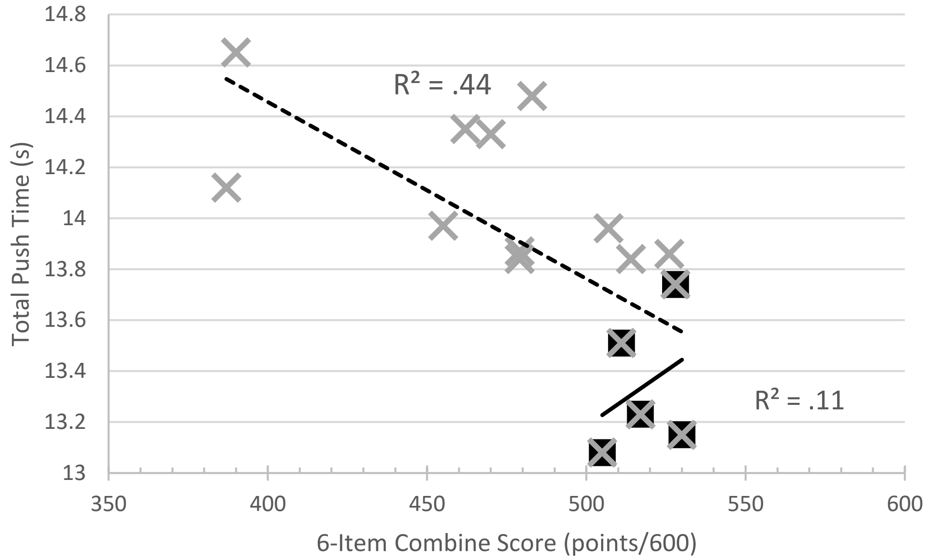


Figure 4.63. NPC 2014, 6-Item Combines scores plotted against total push times presented with linear regressions for TOP10 and ALL, and their respective R^2 values on the graph. Gray "X" and dashed trendline represents ALL athletes. Solid black box and solid black trendline represents TOP10 athletes.

Appendix I

Ancillary Regressions Relating Combine Variables to Total Push Time in 2015 PPC

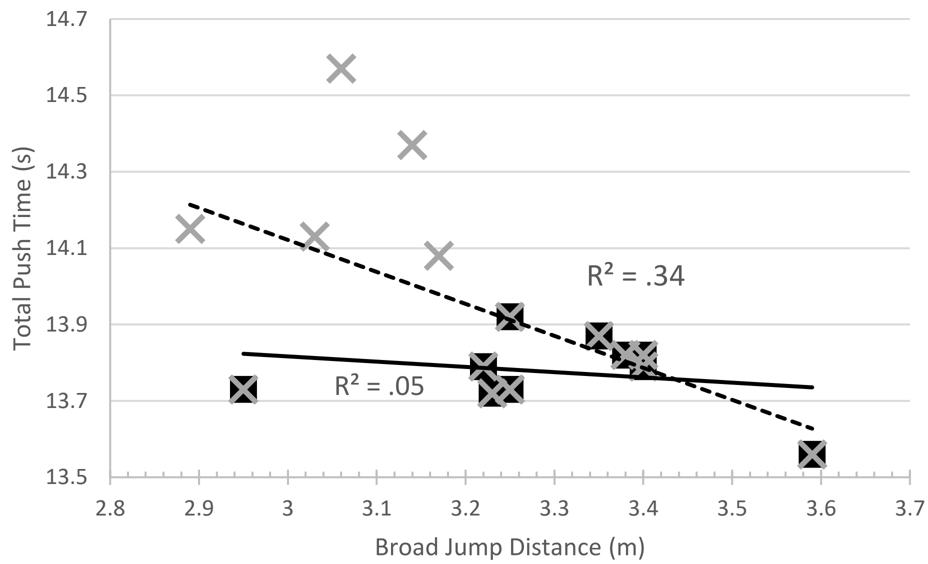


Figure 4.64. PPC 2015, Broad Jump distance plotted against total push times presented with linear regressions for TOP10 and ALL, and their respective R^2 values on the graph. Gray "X" and dashed trendline represents ALL athletes. Solid black box and solid black trendline represents TOP10 athletes.

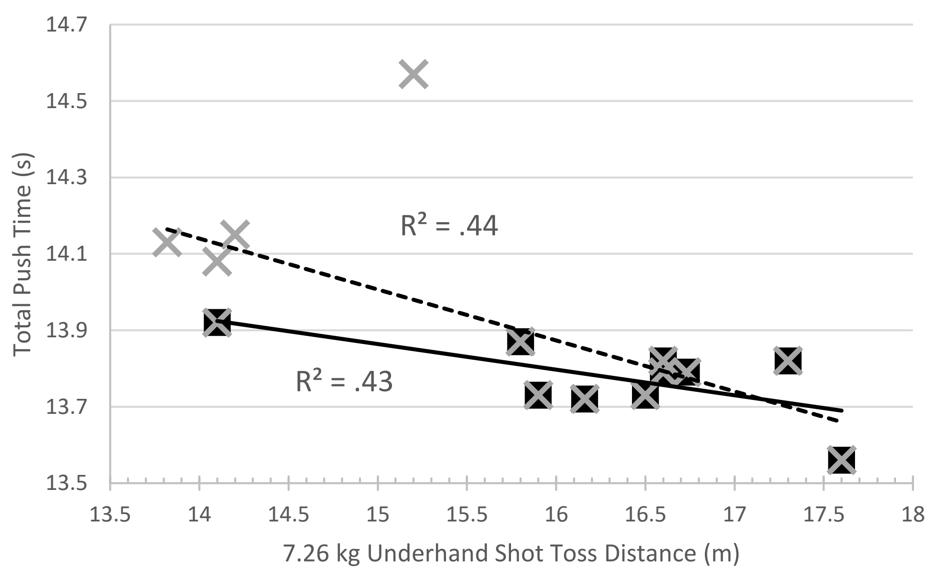


Figure 4.65. PPC 2015, UST distance plotted against total push times presented with linear regressions for TOP10 and ALL, and their respective R^2 values on the graph. Gray "X" and dashed trendline represents ALL athletes. Solid black box and solid black trendline represents TOP10 athletes.

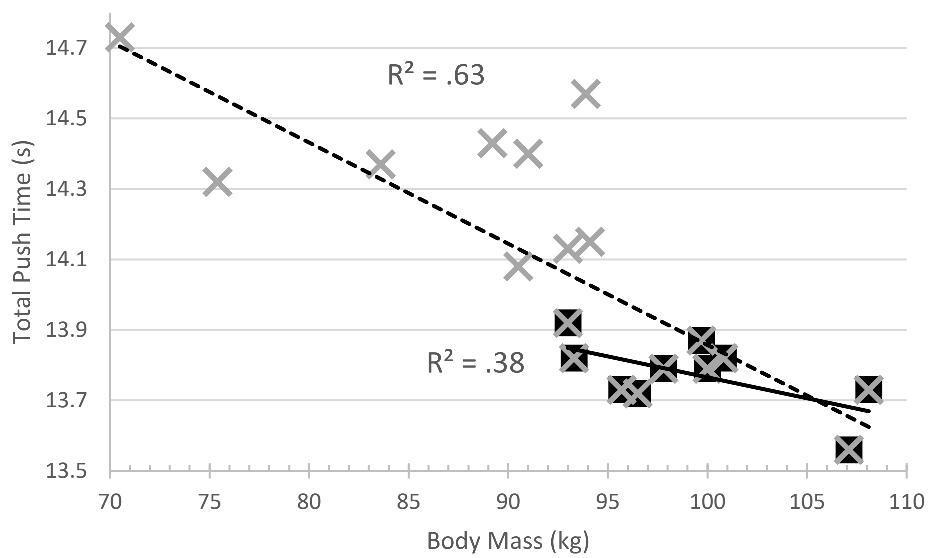


Figure 4.66. PPC 2015, Body Mass plotted against total push times presented with linear regressions for TOP10 and ALL, and their respective R^2 values on the graph. Gray "X" and dashed trendline represents ALL athletes. Solid black box and solid black trendline represents TOP10 athletes.

Appendix J

Ancillary Regressions Relating Combine Variables to Total Push Time in 2015 NPC

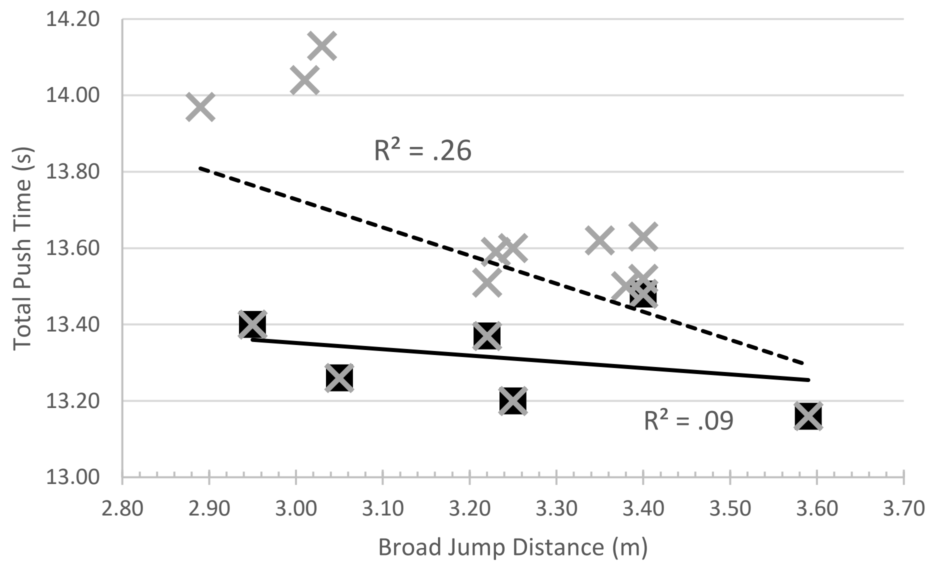


Figure 4.67. NPC 2015, Broad Jump distance plotted against total push times presented with linear regressions for TOP10 and ALL, and their respective R^2 values on the graph. Gray "X" and dashed trendline represents ALL athletes. Solid black box and solid black trendline represents TOP10 athletes.

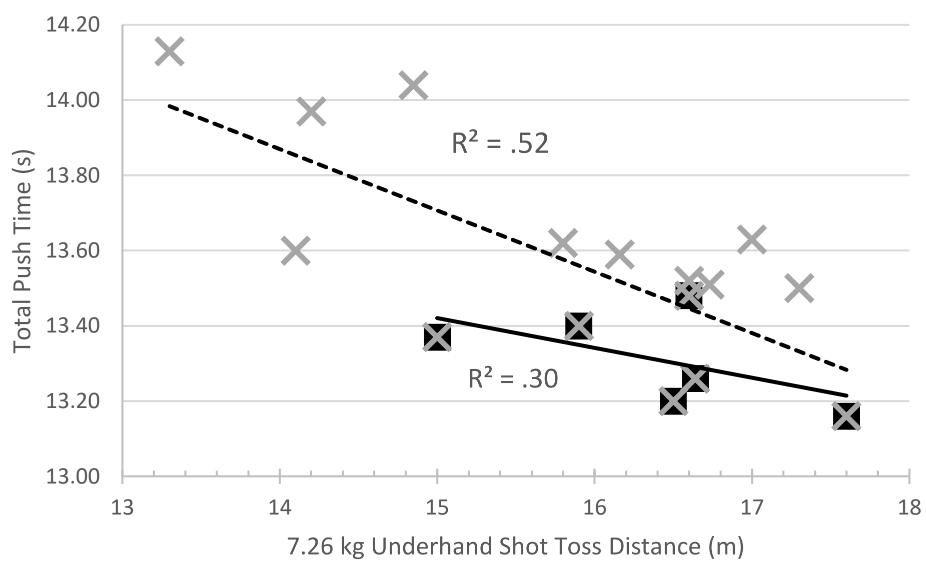


Figure 4.68. NPC 2015, UST distance plotted against total push times presented with linear regressions for TOP10 and ALL, and their respective R^2 values on the graph. Gray "X" and dashed trendline represents ALL athletes. Solid black box and solid black trendline represents TOP10 athletes.

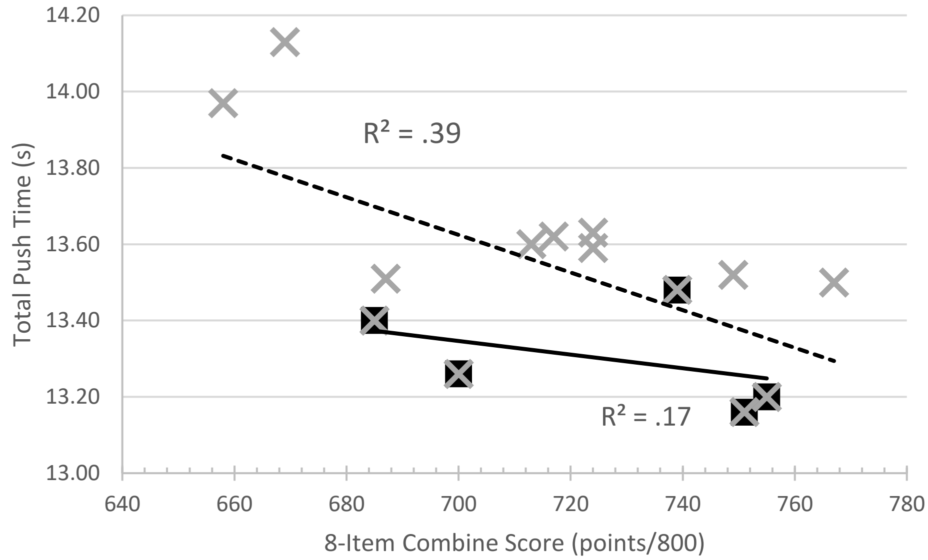


Figure 4.69. NPC 2015, 8-Item Combine scores plotted against total push times presented with linear regressions for TOP10 and ALL, and their respective R^2 values on the graph. Gray "X" and dashed trendline represents ALL athletes. Solid black box and solid black trendline represents TOP10 athletes.

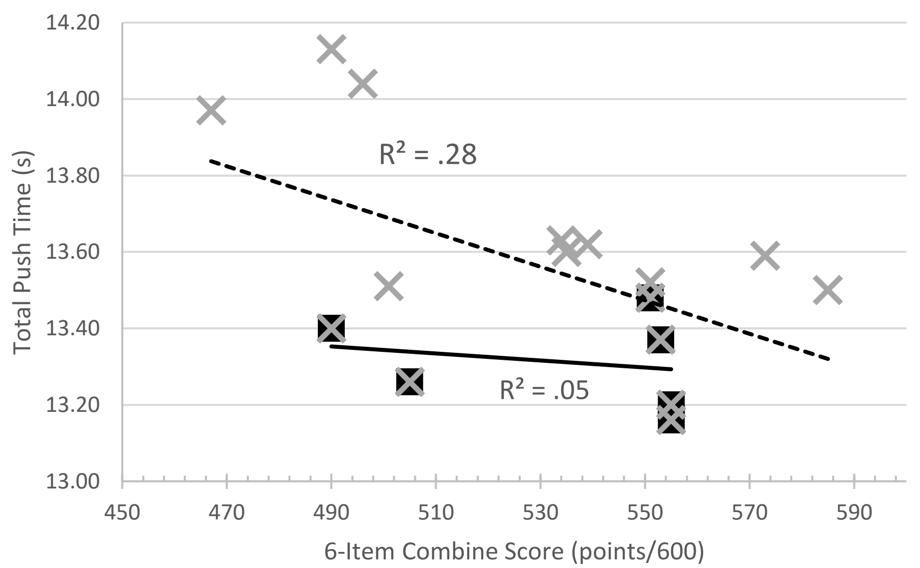


Figure 4.70. NPC 2015, 6-Item Combine scores plotted against total push times UST distance (left) and body mass (right) presented with linear regressions for TOP10 and ALL, and their respective R^2 values on the graph. Gray "X" and dashed trendline represents ALL athletes. Solid black box and solid black trendline represents TOP10 athletes.

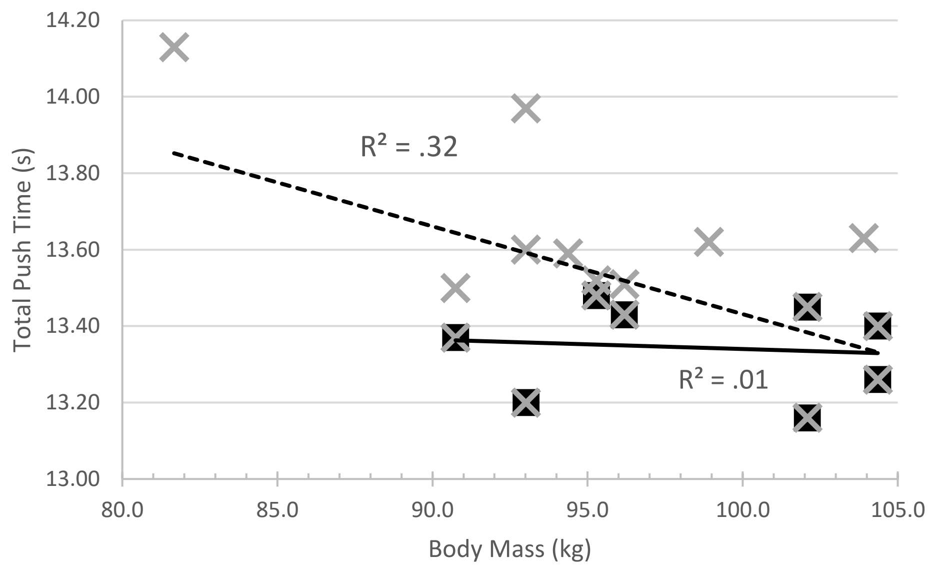


Figure 4.71. NPC 2015, Body mass plotted against total push times presented with linear regressions for TOP10 and ALL, and their respective R^2 values on the graph. Gray "X" and dashed trendline represents ALL athletes. Solid black box and solid black trendline represents TOP10 athletes.

VITA

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Professional Experience:	Fitness Instructor, Personal Trainer, and Weight Room Supervisor, Western Washington University, Wade King Student Recreation Center, Bellingham, WA, 2007 – 2009 PE Activity Course Instructor, Western Washington University, Department of Physical Education, Health and Recreation, Bellingham, WA, 2008 – 2010 Graduate Assistant & Lab Instructor, Western Washington University, Department of Physical Education, Health, and Recreation, Bellingham, WA, 2010 – 2012 Website Manager, Center of Excellence in Sport Science and Coach Education, East Tennessee State University, Johnson City, TN, 2012 – 2013 Course Design Assistant, Online M.S., East Tennessee State University, Johnson City, TN, 2013 Instructor, King College, Department of Athletic Training, Bristol, TN, 2013 Assistant Track and Field Coach, East Tennessee State University, Johnson City, TN, 2012-2014 Instructor, East Tennessee State University, Kinesiology, Leisure, and Sport Science, Johnson City, TN, 2013 Sport Performance Consultant, Renaissance Periodization LLC, New York, NY, 2015 – Current Owner, Excelerate Sport LLC, Snohomish, WA, 2015 – Current

Publications: Harrison, A.P. (November, 2011). Postactivation potentiation (PAP). NSCA Hot Topic Series.

Harrison, A.P. (2015). All You Need To Know About Acceleration: Zero to Sixty With Alex Harrison. Volt Athletics Sport Performance Blog. https://blog.voltathletics.com/home/2015/7/29/improving-acceleration?rq=alex%20harrison

Bazyler, C.D., Mizuguchi, S., Harrison, A.P., Sato, K., Kavanaugh, A.A., DeWeese, B.H., and Stone, M.H. (2016) Changes in muscle architecture, explosive ability, and track and field throwing performance throughout a competitive season and following taper. *Journal of Strength and Conditioning Research, EPAP*

Honors and Awards: Jean Crowell Scholarship Award Recipient ($2200). Western Washington University, Bellingham, WA, 2008

WWU Associated Students Scholar Award Recipient ($500). Western Washington University, Bellingham, WA, 2008

Chappelle Arnett Scholarship Award Recipient ($800). Department of Physical Education Health and Recreation, Western Washington University, Bellingham, WA, 2009

Graduate Assistant ($12,000/year + 75% tuition), Western Washington University, Bellingham, WA, 2010 – 2011

Scholar Athlete of the Year. Athletic Department, Western Washington University, Bellingham, WA, 2010 & 2012

Athletic Scholarship ($2000-$7000/year). T & F, Western Washington University, Bellingham, WA, 2009 – 2012

First Team, All-Academic All-American, NCAA DII, Track and Field, CoSIDA, 2012

Graduate Fellowship ($18,000/year + 100% tuition), East Tennessee State University, Johnson City, TN, 2013 – 2014

USA National Push Championships, 2nd Place USA Bobsled, Lake Placid, NY, 2014

North America Cup Bobsled, Gold in 2-Man Bobsled, Park City, UT, USA, 2014

Bobsled World Championships, 12th and 14th Place in 2- and 4-Man Bobsled, Winterberg, Germany, 2015

USA Bobsled National Push Championships, 9th Place, Calgary, Canada, 2017