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Kinematic and Kinetic Factors Associated with Start Performance in Elite Luge Athletes

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Kinematic and Kinetic Factors Associated with Start Performance in Elite Luge Athletes

by

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Abstract

In the sport of luge, the start phase plays a critical role in overall race performance. However, the biomechanical factors influencing start performance are currently unexplored. The goal of this thesis was to achieve a better understanding of the biomechanics behind the luge start and to validate the use of an accelerometer to assess continuous sled velocity.

It was found that an accelerometer is not a valid tool to evaluate luge sled velocity during the starts. A systematic bias was found in the accelerometer underestimating sled velocity in almost 90% of the trials.

For the pull phase of the start, kinetic variables had a high relationship with pull performance. Gender differences were found in the velocity development and relative force application. None of the hypothesis discussed for the paddling phase were related to performance. However, two very distinct mechanisms in the development of sled velocity were found.

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Dedication

To my family and friends

Table of Contents

List of Tables

List of Figures and Illustrations

List of Symbols, Abbreviations and Nomenclature

Symbol	Definition
3D	Three-Dimensional
r	Pearson's Correlation Coefficient
r^2	Pearson's Coefficient of Determination
ρ	Spearman Rank Correlation Coefficient
ILF	International Luge Federation
IMU	Inertial Measurement Unit
Kg	Kilograms
MEMS	Microelectromechanical Systems
RMS	Root Mean Square

Epigraph

"The struggle itself toward the heights is enough to fill a man's heart.

One must imagine Sisyphus happy."

The Myth of Sisyphus, Alberta Camus

Chapter One: **Introduction**

In the last couple of decades, the latest advances in technology and science has brought a new vision to sports performance. Being the fastest or strongest is no longer limited to natural talent or hard work and sacrifice. Nowadays, decisions are driven by data and empirical support, not only by a simple “gut feeling” or because of the “that is how we have always done it” attitude. In order to succeed in the modern high performance sports’ world, athletes need to have the scientific support from disciplines such as psychology, nutrition, physical conditioning and biomechanics. The difference between winning and losing is defined by centimeters and milliseconds, and that is the edge that sport scientists need to provide to the modern high performance athletes.

Luge is one of the three sliding sport disciplines at the Winter Olympic Games and is one of the fastest sports at the Games. During the Sochi Winter Olympic Games in 2014, the Canadian National Doubles missed a podium position by 0.05 seconds. There are two key elements for performance in luge: the athlete and the sled. The sled depends mostly on the manufacturing and quality of the equipment. Although the rules are very specific on the technical requirements, luge teams are constantly searching for new techniques to improve sled performance to minimize sled-ice friction. Ultimately, the sled will have an important role in the sliding component of the race rather than in the start. The athlete on the other hand, primarily controls what happens at the start and the steering during the sliding phase.

The start phase can be sub-divided into the pull and paddling phases. For the pull portion of the start phase, athletes grasp a set of stationary handles and “pull” attempting to accelerate the sled as much as possible. This is followed by paddling where athletes try to achieve the highest velocity possible by applying forces onto the ice using spiked gloves.

The reason for studying the luge start is because of the crucial role it plays in a luge competition. It is understood both by coaches and athletes alike that the start is a prerequisite for winning a race even though it only makes up five to ten percent of the race time. The start is a highly technical movement where athletes try to achieve the distance in the shortest time possible. Also, this part of the race has the majority of focus during training and is where coaching interventions are applied, specifically during the off season.

Start performance involves a multiplicity of factors, including physiological, psychological, anthropometric and biomechanical. However, the scientific body of knowledge regarding the factors affecting performance in the luge start is fairly limited. Most of the scientific work has been done on the equipment side and very little has been done from a biomechanical perspective.

Therefore, based on the known importance of the start of a luge race and the lack of scientific information available, the main purposes of this thesis were to:

1. Determine the validity of an accelerometer to assess continuous sled velocity during luge starts in flat ice conditions.
2. Determine which kinematic and kinetic factors have an influence during the pull phase of the luge start, and
3. Determine which kinematic factors have an influence during the paddling phase of the luge start in flat ice conditions.

This thesis is broken down into several chapters discussing the above mentioned purposes. Chapter 2 reviews the literature related to the use of accelerometers to evaluate sports performance, the start to final time relationship on winter sliding sports, and the specific scientific information related to biomechanical, anthropometric and physiological factors of the luge start. Chapter 3 studies the validation of a three dimensional accelerometer to calculate continuous sled velocity during luge starts in flat ice conditions. Chapter 4 investigates the kinematics and kinetics of the pull phase. Chapter 5 investigates the paddling phase and the kinematics related to performance. A summary of the results, discussion, limitations and future directions is provided in Chapter 6.

Chapter Two: **Literature review**

The literature review focuses on three important topics. The first topic encompasses the summary of knowledge related to the use and application of accelerometers and inertial measurement units (IMUs) to evaluate sports performance; more specifically how these devices have been used to calculate velocity from acceleration and other signals. The second topic focuses on the existing literature related to how the start times are related to the final times (competition times) for the sports of luge, bobsleigh and skeleton. The final topic summarizes the scientific literature related to the start phase in the sport of luge and the biomechanical factors associated with luge start performance.

2.1 Accelerometers, IMUs and Sports Performance

In recent years, the use of accelerometers has increased in popularity among sport scientists due to the fact that these systems are inexpensive, non-invasive and wireless. There are several types of accelerometers in the marketplace, which include strain gauge, piezoelectric and piezoresistive based systems. The most recent introduction of accelerometer technology into the marketplace is the microelectromechanical systems (MEMS), which is a technology that may be considered superior at a reduced cost, smaller size and an improved accuracy to the previous accelerometer technologies. Inertial measurement units are composed of an accelerometer, a gyroscope and sometimes a magnetometer.

However, accelerometers have limitations depending on the application that the device will be used for. Three-Dimensional (3D) accelerometers sense the gravitational acceleration (Ladin

& Wu, 1991), which could introduce a significant amount of error to the acceleration signal, depending on the orientation and mounting of the sensor. In the mobile devices industry it seems to be a benefit as accelerometers are used to estimate the tilt and roll of a device based on the gravity vector.

An extensive amount of scientific literature has dealt with other issues while using accelerometers including noise and drift. Djuric (2000) discussed the sources of noise in MEMS devices. Examples of the different types of noise in MEMS technology can include thermal and electrical noise, which are caused by the design and manufacturing components of MEMS devices (Djuric, 2000). As a consequence of the noise collected in the accelerometer signals, velocity and position estimation, which is achieved by mathematically integrating and double integrating an acceleration signal, tend to accentuate the errors. Even in a static situation, accelerometers drift and can be inaccurate in calculating the sensor position. It has been shown that the error increases with integration time and a higher sensor sampling rate (Thong, Woolfson, Crowe, Hayes-Gill, & Challis, 2002).

Accelerometers have been used in gait analysis to successfully estimate stride length. The issue of drift and the error in velocity and position estimations has been solved by the assumption of a zero velocity of the foot during the stance phase in the gait cycle (Peruzzi, Della Croce, & Cereatti, 2011; Sabatini, Martelloni, Scapellato, & Cavallo, 2005). By providing a known zero velocity value for the start of the integration interval and reducing the integration time to a fraction of a second, accurate values of velocity and distance have been successfully achieved for running and walking movements (Peruzzi et al., 2011; Sabatini et al., 2005).

Accelerometers have been used for a variety of applications by sports scientists, including, the quantification of stride frequency during sprinting (Neville, Rowlands, Wixted, & James, 2011), estimating weightlifting training load and barbell kinematics (Caruso & Olson, 2012; Sato, Sands, & Stone, 2012; Sato, Smith, & Sands, 2009) and evaluating and assessing swimming mechanics (Callaway, Cobb, & Jones, 2009).

Dadashi, Crettenand, Millet, and Aminian (2012) utilized an IMU containing a 3D accelerometer and 3D gyroscope attached to the subject's sacrum to estimate swimming velocity. The results showed a difference of 0.6 ± 5.4 cm/s for the mean cycle velocity between the IMU and their reference velocity measured with a tethered speedometer. The authors utilized the pool length as a correction factor on the mean lap velocity to eliminate the drift issue from the IMU. The results from this study seem promising for velocity estimations but only when prior knowledge is involved and correction factors are included in the velocity calculation.

In a recent study, F. Dadashi, Millet, and Aminian (2014) utilized a Bayesian linear regression method to estimate breaststroke swimming velocity using input data from an IMU for cycle velocity estimation. Results indicated there was an average relative error of 0.1± 9.6% between the reference velocity and the estimated velocity from the Bayesian linear regression model. This approach taken by the investigators resolves the drift issue by avoiding the integration of the acceleration signal while using the IMU data as a predictor of swimming velocity. Although the results from this approach appear to be encouraging, the correlation between the Bayesian approach velocity and the reference system was 0.91, which still leaves a considerable amount of error in this method particularly for the velocity estimation of high performance swimmers. Also, the correlation coefficient dropped to 0.82 when the number of predictors in the Bayesian linear regression was reduced from 9 to 5.

Gaffney, Walsh, O'Flynn, & O'Mathúna (2013) assessed performance in winter sliding sports by using a wireless IMU instrumented on a Skeleton training sled to collect data related to start performance. Velocity curves calculated from the integration of the acceleration signal showed an average velocity error of 0.462 ± 0.248 m/s, which corresponds to a relative error of 7.57± 4.12 % compared to the reference velocity from timing lights and video data. In the trials with the best correlation, sled velocity difference was of 0.176± 0.143 m/s (2.97± 2.63%) and 0.800± 0.251 m/s (13.2± 3.55%) for the trials with the worst correlation. As stated by the authors, the magnitude of the error is unsatisfactory for the evaluation of top-level skeleton athletes.

Gaffney, Walsh, O'Flynn, & O'Mathúna (2015)instrumented a Skeleton start training device with wireless IMUs to accurately measure sled velocity during skeleton start training. The training device consisted of a skeleton sled attached to and running along a pair of 3m rails. The sled had padded shoulder attachments from where the athletes performed their sprint and pushed the sled. The results indicated an average Root Mean Squared Error of 0.105 m/s compared to the average velocity calculated from timing lights. For this particular application, knowing the total distance traveled by the sled (3 meters) and short-time integration periods assisted in accurately estimating velocity and resolving the drift issues associated with IMUs. Also, the velocity obtained from an IMU was not compared to a reference continuous velocity profile but to the average velocity estimated from timing lights. As a consequence it cannot be concluded if the velocity from the IMU was accurate throughout the continuous velocity data. The average velocity estimated from the IMU could be the combination of many different resultant velocities measured with the sensor.

The application of the abovementioned methodology to other potential applications such as on ice-track testing or other winter sliding sports is difficult. In winter sliding sports the total distance traveled by the sled during the start is generally unknown and usually more than 3m (in skeleton and bobsleigh the “loading” phase could occur somewhere in between 30-50 meters from the start; in the sport of luge this distance is shorter and could range from 7- 15 meters) and as such the integration time is larger than just a few seconds. Thus, it is not possible to use the previously mentioned strategies to correct accelerometer drift-related issues and generate accurate and meaningful results.

Roberts (2013) also instrumented a skeleton sled with an accelerometer to obtain sled velocity data. In this study, the author collected the data in an indoor setting using an ice start ramp and the start ramp was equipped with timing lights every 10 meters. For validation purposes, the author utilized the information of the timing system to re-calibrate the accelerometer for every 10-meter split. From the continuous velocity profile, the researcher identified multiple performance indicators with respect to the total start time. The author also described several different loading techniques that could be recognized in the velocity signal. Nevertheless, the author did not report the accuracy of the accelerometer with regards to the reference system.

Most of the drift-correction techniques mentioned in the literature utilize some sort of a priori knowledge to improve the accuracy of the data collected and processed from the sensors, whether it is using another system such as timing lights or knowing the overall displacement of the object being measured. In many situations, this a priori information is not available and the use of timing systems is not possible. The particular purpose of this thesis is to validate a three dimensional accelerometer without using any other supportive system. In the author’s opinion, for the development of measuring techniques and testing protocols, the ease of use is fundamental to include the methodology and instrument in the daily training environment for the use by athletes.

2.2 Start Performance Time to Total Event Time: The Relationship in Winter Sliding Sports

There are 21 tracks listed under the International Luge Federation website (ILF, 2015) that are used and have been used for competition purposes. All of the tracks vary in total length, average grade, vertical drop and length and inclination of the start ramp. According to the ILF rules (ILF, 2015), luge tracks need to between 1,000-1350 m long for men singles and between 800-1350 m for women, men's doubles and juniors. The Koenigssee track in Germany has a total length of 1,362 m (the Koenigssee track has an exceptional longer length approved by the ILF; ILF Rules Supplement 1, 2014)) for men's single and the Calgary track in Canada has a length of 1251 m. In the case of women and men's doubles, the placing of the start house is further down the track. In every competition, five interval times are recorded during a race: a start time, three intermediate times and a final time. A tenth of a second can determine the difference between winning or losing a luge race. During the last Winter Olympic Games in Sochi, the cumulative time difference after four runs between the 3rd and 4th place in men's doubles was of 0.05 seconds (FIL, 2014). Thus, it is crucial to maximize performance in each segment of the track to be successful.

The first scientific study analysing the start time to final time relationship in winter sliding sports dates from the 1988 Calgary Olympics. Morlock and Zatsiorsky (1988) showed the influence of the start on the performance time for the 4 man bobsleigh competition. Multiple correlations were performed comparing split times to the overall time. It was found that the 10 meter split time had the highest correlation with final time. This indicated the necessity of bobsleigh athletes to accelerate the sled as quick as possible from the beginning of the start. In addition, the effect of starting order and ice temperature on performance outcome was also shown in the study, leading to modifications on the luge, bobsleigh and skeleton rules in relation to start order.

In a study performed during the 1994 Winter Olympic Games in Lillehammer, Brüggemann, Morlock, and Zatsiorsky (1997) demonstrated the influence of the start time on final race time for the men's luge when all the athletes were considered ($r^2 = 0.55$). However, when the authors included only the top 15 finishers in the analysis, this relationship was not significant. For the Lillehammer track, the start time may be a condition for winning the race but ultimately the sliding component is the deciding factor for the luge men's competition. Similarly, there was a significant relationship between start time and final time for 2 men and 4 men bobsleigh, which also diminished in the 2 men bobsleigh when only the top 15 athletes were considered.

Fedotova (2010) studied the relationship of the track interval times for men's luge single and skeleton competitions at the Lake Placed track in the USA and the Whistler track in Canada. The influence of the start interval on the total time for the luge men's single on these two tracks was not significant, with a Kendall-Tau Rank correlation coefficient of 0.46 for the Whistler track and 0.18 for the Lake Placid track.

In the case of skeleton, conflicting results have been reported. Zanoletti, Torre, and Merati (2006) found low to moderate correlation coefficients in skeleton between start time and final time for men (r=0.48) and women (r=0.63) when analysing data from several tracks during the 2002-2003 and 2003-2004 seasons. In an analogous study, the correlation coefficient between start time and final time for skeleton were small but seemed to be related to the technical difficulty (driving component) of the track (Bullock, Hopkins, Martin, & Marino, 2009). Likewise, for the Lake Placid and Whistler tracks for skeleton competitions, the impact of the start phase on final performance was not significant (Fedotova, 2010). Moreover, Bullock et al. (2008) analysed in more detail the women's skeleton start and found a very high correlation between the velocity at the 15 meter mark and start time for the Sigulda and St. Moritz tracks. Thus, for female skeleton athletes it is vital to accelerate as much as possible during the first 15 meters to be successful in the start. This could be an important parameter for field testing and talent identification.

The International Luge Federation states that the luge start ramp must have a minimum length of 10 meters and maximum length of 30 meters with a gradient varying between 20% to 25% and having a maximal track entry angle of 8 degrees (IFL, 2014). These diversities in start ramps plus the different track geometries partially explain the variability in the start time to final time relationship across the different tracks. Also, the start ramp conditions could influence the athlete's race strategy. For example, lugers who are better at the paddling phase may perform better in a flat long start, whereas athletes who excel at the pulling will benefit from steep and short start ramps.

Although the location of the start house is not the same for luge and skeleton, Bullock et al (2008) showed how skeleton athletes adapt their start mechanics to the start ramp characteristics. In St. Mortiz, 14±1 steps were performed before the load, whereas in Lake Placid and Sigulda the number of steps was of 18±1 and 17±2 respectively. According to the authors, Lake Placid presents a long and flat ramp; Sigulda has a short and steep start, and in St. Moritz the first curve of the track is close to the start. It seems that in St. Moritz athletes need to adapt the race position sooner than in the other tracks, which may be the reason why the number of steps during the sprint are less (Bullock et al., 2008).

When investigating the influence between start time and final time, other factors need to be taken into consideration. First of all, environmental conditions change from year to year. This is especially true for the ambient temperature, which modifies ice temperature thus affecting the coefficient of ice friction between the ice and the steel runners. Also, the presence of snow in the track can be a severe detriment to performance in winter sliding sports.

The majority of the studies mentioned above retrieved the competition results and timing data from third party sources such as the official website from the various sports organizations. In the particular case of Luge, the first light-trap initiating the timing system has to be 5-10 meters from the start handles and the total start time has to exceed three seconds. When the time to the next timing light does not reach three seconds, the start time has to be taken after the first curve. If this is the case, there are other variables that might be playing a role in the documentation of the start time other than just the athlete’s starting technique and performance. It would be useful, at least during training runs before the actual competition, if multiple split times were collected and reported along the start ramp so that athletes and coaches could identify the part of the start (pull, paddles or laydown) that is leading to a good or bad performance. That way they could identify problems in performance and make modifications to their start strategy (e.g. modifying the number of paddles, paddle frequency or laydown technique).

Finally, winter sliding sport tracks are usually subjected to structural alterations, either on the length of the start ramp, slope of the ramp or a change in the physical location of the start house. For example, after the fatal luge accident during the 2010 Winter Olympics in Vancouver, the luge start house for the men’s discipline was moved further down the track to the women’s and the double’s start house, while the women’s and double’s start house was relocated to the junior’s start house (Reich, 2010). Changing the start house location appears to modify the geometry and characteristics of the track based on data from previous years.

The current state of the literature shows the relevance of the start phase on winter sliding sports and overall performance. The association between these two variables appears to vary across the different venues. Despite the scientific literature, coaches and athletes know that maximizing performance at the top of the track is a pre requisite for a successful run. The driving component and the interaction of the equipment with the ice surface are probably the ultimate deciding factors in performance. However, it is unlikely that the driving alone will compensate for an unsuccessful performance at the start ramp.

2.3 Physiological, biomechanical and anthropometric aspects of the Luge Start

Besides the existing limited scientific literature establishing the association between performance outcome and start time in winter sliding sports, both coaches and athletes understand the relevance of the start phase in winter sliding sports and spend most of their pre-season training improving their physical strength and starting technique. However, most of the research on these winter sports has been centred on the design and optimization of the equipment (P. Dabnichki, Motallebi, & Avital, 2004; Poirier, Maw, Stefanyshyn, & Thompson, 2009), sled turning dynamics and track simulations (Braghin, Cheli, Donzelli, Melzi, & Sabbioni, 2010; Braghin, Donzelli, Melzi, & Sabbioni, 2011; Hubbard, Kallay, & Rowhani, 1989; Kelly & Hubbard, 2000; Levy & Katz, 2007; Mössner, Hasler, Schindelwig, Kaps, & Nachbauer, 2011), sports specific physiological testing (Kibele & Behm, 2005), bobsled aerodynamics (Berton, Favier, Agues, & Pous, 2004; Peter Dabnichki & Avital, 2006), sport related injuries

(Cummings, Shurland, Prodoehl, Moody, & Sherk, n.d.; Reid, 2003; Severson et al., 2012) and the interaction between the sled and the ice friction coefficient (Fauve & Rhyner, 2008; Poirier, Lozowski, Maw, Stefanyshyn, & Thompson, 2011). Surprisingly, in winter sliding sports, the study of the start phase biomechanical components and potential performance indicators has been the subject of only a handful of publications. For instance, in the sport of bobsleigh there is only one known scientific publication on a kinematic analysis of the start phase (Smith, Kivi, Camus, Pickles, & Sands, 2007).

The luge start phase can be divided in multiple phases; Kempe and Thorhauer (as cited in Platzer, Raschner, & Patterson, 2009) divided the start phase in five consecutive stages (Figure 2-1 and Figure 2-2):

1. Forward rocking of the sled while holding the start handles, also known as “load”.
2. The compression phase, involving a backwards movement of the sled.
3. Push off from the start handles or “pull”, where athletes attempt to accelerate the sled as much as possible.
4. Multiple cyclical arm strokes consisting of the paddles.
5. “Laydown” which is essentially assuming a race position.

Figure 2-1. First 4 phases of the luge start (from left to right) load, compression, pull and 1st paddle during a flat ice training session.

Figure 2-2. Following phases after the first paddle, the athlete performs a second, third and fourth paddle before assuming the race position or laydown.

It can take several years to master the start technique in luge, unlike bobsleigh and skeleton where athletes usually “transfer” to these sports at a later age from another sport. Usually the sport from where bobsleigh or skeleton athletes originate involves sprinting as a key component such as 100 m discipline in track and field or American Football (Bullock, Gulbin, et al., 2009; Collins, Collins, Macnamara, & Jones, 2014). In bobsleigh and skeleton the strength-power of the lower extremity and sprinting ability seems to be a higher predictor of start performance (Osbeck, Maiorca, & Rundell, 1996; Sands et al., 2005). Luge athletes are taught the fundamentals of start technique from a very young age and it is a major component of their training until they have acquired the proper body mass and muscular strength to focus their training on the sliding component of luge.

In terms of the physiological and strength requirements of the luge pull phase Platzer, Raschner, and Patterson (2009) studied the relationship of several strength measurements and anthropometric variables with maximum speed and end speed (i.e. sled speed at the point where the athlete releases the start handles). Thirteen male lugers that were part of the Austrian National luge team took part in this study. Results from the multiple linear regression analysis generated a model with maximum isometric bench pull strength as the predictor ($R^2 = 0.750$) when maximum speed was the dependent variable. Relative isometric bench pull strength (normalized to body mass in Kg $^{0.67}$) was the highest predictor when end speed was the dependent variable ($R^2 = 0.731$). Stature ($R^2 = 0.532$), body mass ($R^2 = 0.405$) and eccentric speed ($R^2 = 0.542$) appeared to also have a relationship with maximum speed during the pull phase, although body mass and stature did not seem to influence the end speed of the pull. The mean and standard deviation of the maximum speed was 4.02±0.34 m/s and of 3.52±0.28 m/s for the end speed. A paired *t*-test analysis indicated that the end speed was lower than the maximum speed.

As Platzer et al. (2009) pointed out, the relationship between body mass and maximum speed explicated by the impulse-momentum relationship (for example, if the sled's weight is similar to all athletes, to a lighter athlete the sled is heavier relative to the athlete's mass compared to a heavier athlete assuming that both athletes have a similar relative force to their body mass) could be an imperative criteria for athlete selection and talent identification.

All sleds and athletes are weighed before each competition. In winter sliding sports, the total mass of the sliding system (sled + athlete) is a fundamental factor for performance. The sled mass is required to be 21-25 kg and 25-30 kg for singles and doubles respectively (ILF, 2014).

Additional weight can be carried by the luger following a certain criteria: singles men are allowed to carry 100% of the difference between the athlete's body weight and a reference body weight of 90 kg, with a maximum additional weight of 13 kg. Women single athletes have similar conditions but with a baseline body mass of 75 kg and maximum additional weight of 10 kg. Doubles, can add 75% of the difference from a 90 kg reference weight with a maximum of 10 kg but are not permitted to add extra weight if the weight of the two athletes surpasses 180 kg. Extra weight cannot be added into the sled and it has to be strapped around the torso of the athlete.

Crossland & Hartman (2011) examined the association between multiple strength tests and anthropometric measurements with luge start performance times in an indoor testing facility. The statistical correlation revealed significant Pearson's correlations for eight different tests in the case of the Senior National Team and three significant Pearson's correlations for three tests on the Junior National Team. This study found similar results to the study from Platzer et al. (2009), as the prone row one maximum repetition and weighted pull up maximum repetition had the highest correlation (r =-0.82 and r-=-0.81) for the Senior National Group. The 1 repetition maximum bench press also presented significant results with a high correlation coefficient (r = -0.76). In the case of the National Junior Team, bench press maximum repetition and prone row maximum repetition presented the highest and identical correlation coefficient with start times (r = -.076). From the anthropometrical variables, the acromion-olecranon length had a significant relationship with start performance times on both groups, being of -0.74 and -0.58 for the Junior Team and National Team respectively. Biacromial breadth and height had moderate statistically significant correlation coefficients, r = -0.71 and r =-0.62 for the Senior National Group. The lack of statistical significance in the National Junior Team Group could be related to the sample size in this group (n = 9), compared to the 13 subjects present on the Senior National Team Group.

Both of these studies demonstrate the importance of upper body strength on luge start performance, specifically the muscles involved in the pulling action. In the study from Crossland and Hartman (2011) their results are in agreement with Platzer et al. (2009), but it is uncertain as to which particular part of the start (pull phase or paddles) their results apply as their testing outcome variable was the total start time. Future studies looking into the strength requirements of the sport of luge should also focus on evaluating muscular power of the upper extremity muscles due to the explosive nature of the luge pull start action.

With regards to the pull phase of luge, Fedotova and Pilipiv (2012) described a case study of the kinematics of the pull phase. In this case study, the authors describe different pulling techniques by three experienced female lugers. Parallel to the results from Platzer et al. (2009), the three athletes reached a maximum velocity which occurred from the compression to the pull before the hips crossed the start handles, followed by a drop in velocity at the end of the pull. Platzer et al (2009) attributed this decrease in velocity to a lack of strength in the wrist flexors and arm extensors or possible technical flaws. In two athletes, a decrease in hip and shoulder vertical velocity was related to the decrease in horizontal sled velocity after reaching the peak sled velocity. In one of these two athletes, a higher negative hip horizontal velocity relative to the sled produced a longer and steeper loss in horizontal sled velocity after reaching the maximal sled horizontal velocity. The third athlete, did not reach a horizontal maximal velocity as high as the other two athletes, but peaked after reaching the maximal sled velocity and utilized the forward movement of the hips relative to the sled to increase the sled velocity.

Fedotova and Pilipiv (2012) described starting kinematics of a very heterogeneous sample of female lugers (age range was 19-37 years old). They used a descriptive analysis due to logical sample size problems. Thus, the applicability of their results to other luge athletes is problematic. Nevertheless, this is one of the only studies providing some scientific insight into the biomechanics of the pull phase in the sport of luge

In another case study, Fedotova and Pilipivs (2010) analysed the timing and kinematics of the preparatory movements during the pull phase between a training scenario and competitive events in two female and one male junior lugers. The preparatory movements consisted of the forward motion ("load") and the backwards motion ("compression") of the sled. Only the male athlete had a significantly faster start time during the competition. One of the female athletes performed better during training, which was associated with increases in the time from load to compression (T1; first to second figure on Figure 2-1) and from load to where the athlete's hips crossed the start handles (T3; figure 2 to figure 3 on Figure 2-1). In contrast, the male athlete had a significantly smaller T1 and T3 resulting in a better performance in competition.

This study also looked at the kinematics and more specifically the angle between the trunk and the thigh. This variable was significantly different in competition across the three athletes at the moment T3, representing a larger magnitude in trunk extension. It is unknown if this greater magnitude in trunk extension represented an improvement in pull performance considering that only the male athlete achieved better results. Interestingly, the athlete who had worse performances during competition showed overall the largest kinematic variability, at least in terms of the trunk flexion-extension.

Another fact to distinguish from the work of Fedotova and Pilipivs (2010) relates to the gender differences between female and male lugers. The time T2, which represents the moment where athletes apply force in the forward direction to accelerate the sled, was not substantially different between the two groups (0.58 and 0.57 for the females, 0.56 for the male). If the horizontal impulse determines the change in linear momentum and the sled horizontal velocity at the release from the handles, then it is probable that a higher horizontal impulse achieved by the male athlete is being accomplished by a larger magnitude in the horizontal force and not by the time of force application. Even more, T2 was smaller in the case of the male compared to the two females.

Regarding the paddling phase of the luge start, Lembert, Schachner and Raschner (2011) discussed the design, instrumentation and implementation of a training simulator for the luge paddles. Turk-Noack (1991) (as cited on Lembert et al., 2011) stated that 23% of the total start performance is contributed by the paddle phase. According to Lembert et al (2011), for an efficient paddling technique, athletes need to keep the fingers, wrist and elbow joints stiff to transfer force into the ice and through each paddle increase their momentum achieving maximal speed at the end of the paddle's cycle. Muscles of the torso also need to be tight to keep the back straight as the luger reaches forward with the arms at the swing phase.

The paddle training simulator consists of an aluminium frame with a luge seat in the centre of two conveyor belts operated by two servo motors. The simulator, also known as "Speed Paddler" (Lembert et al., 2011) provides instant feedback on torque production and possible left to right wrist asymmetries to athletes and coaches. The same asymmetries detected with the Speed Paddler were also found during actual track starts. Asymmetrical paddles are considered a technical flaw and may lead to lateral movements of the sled, which could lead to hitting the start ramp wall (Lembert et al. 2011). Different start ramp inclinations can be simulated and athletes achieve velocities similar to race conditions. The resistance of the simulator can also be changed to train at higher loads and at different movement speeds. Other than discussing the application of the Speed Paddler as an effective training tool to detect efficient or deficient paddling techniques, the article does not bring any other insight to the paddling mechanics or performance indicators that could be implemented in the coaching process.

During the off season (summer time), it is impossible for luge athletes to train on actual luge tracks. As a result, coaches need to be creative and find different resources to recreate track conditions, in particular to train the start phase. The scientific literature refers to different solutions that include wheeled sleds (Hancock, 1988), start training simulators (Lembert et al., 2011; Platzer et al., 2009) and even indoor luge start iced ramps (Crossland & Hartman, 2011; Fedotova & Pilipiv, 2012). Even if the tracks were available, it would not be practical if coaches just wanted to focus on the start technique to slide all the way down the track every time the athlete desires to practice the start. This lead to the advent and use of indoor training facilities with start ramps and real ice for athletes to train in close to competition environments all year round.

However, the architecture of the indoor facilities needs to be taken into consideration to re-create optimal training conditions. Fedotova and Pilipiv (2011) found significant differences when analysing the timing patterns of the start on an iced start ramp compared to an outdoor luge track. The compression time was larger in the indoor start ramp compared to the actual track. In this particular start ramp the handles are closer to the beginning of the track and athletes felt restricted and were more cautious during the compression phase, affecting the timing and speed. Luge coaches have the belief that a shorter compression distance influences pull performance. From a theoretical standpoint this belief seems reasonable as a shorter compression distance results in reduced path to accelerate the sled forward. Platzer et al. (2009) also supported this idea as they found a moderate relationship between eccentric speed (speed at the compression) and maximal speed at the pull.

In addition to the modifications on the compression, Fedotova and Pilipiv (2011) reported a significant difference in the timing between the paddles when comparing the results from the track to the start ramp. It appears that during competition, some athletes decreased the duration of the paddle cycle (from contact with the ice to the next contact with the ice), which could be associated with getting into a race position or "laydown" in time (Fedotova and Pilipiv, 2011). The different characteristics between the start ramp and the actual track start could also influence the paddle frequency, which they did not report in the study. It is essential to clarify that these results can only be interpreted and apply to the start ramps that were used in this study. There was no information related to the specifics (geometry) of the start ramps.

The use of iced start ramps is part of a luger's daily training routine, hence the importance of simulating conditions to the competition track start ramps and identify any potential sources that could affect the athlete's technique. Alterations to starting kinematics on artificial start ramps are of special interest for this thesis as part of the kinematics and kinetic of the luge start will be studied at the start ramp in the Ice house at Canada Olympic Park.

Clearly, the start phase in luge and the other winter sliding sports has been a matter of interest for sports scientists. It seems contradictory that the majority of the published research has focussed on the equipment side of the sport instead of investigating the biomechanical factors related to successful start performances in order to apply effective coaching interventions and improvements in start performances.

In this literature review, three different topics were covered related to this thesis. The first topic discussed the application of accelerometers and IMUs to estimate velocity and evaluate sports performance. The impact of the start phase on final race time in luge and winter sliding sports was discussed in the second part. Finally, the last topic covered physiological, anthropometric and biomechanical factors associated with start performance in luge. These three topics are vital to address the main purposes previously presented in the introduction of this thesis.

Chapter Three: **Validation of a tri-axial wireless accelerometer to assess continuous sled velocity during luge starts**

3.1 Introduction

In the sport of luge, a thousand of a second determine the difference between winning and losing a race. Both coaches and athletes alike believe in the importance of having a good performance at the start and the limited scientific literature available related to measurement of performance at the start also corroborates this concept (Bruggemann et al., 1997). Thus, it is fundamental to have a precise and valid method to assess sled velocity during the start phase, in particular during the athlete's technical preparation phase, or prior to the competition season.

Accelerometers and their application for assessing sports performance were discussed in the literature review. These sensors are extremely popular amongst sports scientists. They are non-invasive, wireless, inexpensive, compact and can record data at high sampling rates. Researchers have used accelerometers to calculate velocity and displacement from the acceleration signal. Validation studies in similar applications (for example in skeleton start training), showed a relative average error of 7.57± 4.12 % between the velocity estimated with an IMU and the reference velocity (Gaffney et al., 2013).

In the current state of accelerometer and MEMS technology, noise and drift are present in the acceleration signal, making the calculation of accurate velocity values very challenging. Even more, as accelerometers also measure the gravitational field acceleration, improper mounting methods will also result in inaccurate velocity measurements.

Sports scientists have adopted different strategies to resolve the drift issue. Most of the potential solutions involve either a priori knowledge of the distance the athlete or the object being measured is going to travel, or using timing systems at fixed distances and intervals to correct the velocity calculation. The first solution is not feasible in the particular case of luge as the total distance the sled will travel is unknown. Utilizing an additional timing system would be limited only to training circumstances or using the timing system present on the track if the distance between timing lights is known.

The usual method to evaluate performance on flat ice conditions are timing lights. The quantitative and qualitative information that this method provides is fairly limited. An accelerometer could potentially estimate continuous velocity accurately during the luge pull starts providing much more information than the timing lights. Thus, the aim of this chapter is to assess the validity of a three dimensional wireless accelerometer to estimate horizontal sled velocity during luge pull starts on flat ice.

3.2 Methods

3.2.1 Participants

3.2.1.1 Convenience Sample

A total of nine luge athletes ranging in ages from 18 to 27 participated in the data collection sessions. Seven subjects were part of the national luge team and two subjects were part of the developmental team. Therefore, all participants were very experienced luge athletes with thousands hours of experience in pull starts. Five of the participants were male with an average age $M_{age} = 20.4$ and the other four participants were female with an average age $M_{age} = 23.5$.

All the recruitment took place through the Canadian National Team coach who informed the investigators about the athlete’s availability based on their competition calendar. Once the

National Team Coach determined the availability of the participants, the investigators contacted the athletes.

3.2.1.2 Inclusions

Athletes who trained at Canada Olympic Park in Calgary, Alberta, members of the national luge team and were injury free at the moment of the study were included in the study.

3.2.1.3 Exclusions

Subjects who did not compete during the last calendar season (2013-2014) were not included in the study.

Two of the trials were rejected for analysis because the athlete did not follow the instructions from the investigators. The subjects did not remained steady during the quite period required to calculate correctly sled velocity.

3.2.1.4 Sample size and power

Based on the athlete's calendar and time availability, four athletes were available to participate in the initial data collection sessions of this project. During the third phase of this study, accelerometer data and motion capture data were also collected on another five subjects following the same data collection procedure as described in the following methods section.

A sample size calculation and power analysis was not performed as the sample size is limited by the nature of the population.

3.2.2 Equipment

3.2.2.1 Accelerometers

Two three dimensional wireless accelerometers of the same make and model (G-Link XLRS, Lord Microstrain; Williston, VT, USA) were used to obtain 3-D acceleration data of the sled during luge starts (Figure 3-1). The sensor was secured under the sled using industrial strength Velcro with adhesive.

Figure 3-1. Microstrain G-Link LXRS wireless accelerometer.

The accelerometer communicated wirelessly to the computer through a base station, thus data were transmitted after every trial and downloaded to the computer. The software provided by the manufacturer of the accelerometer (Node Commander, Lord Microstrain; Williston, VT USA) was used to initiate the data collection and download the data from the units.

3.2.2.2 Portable Luge Start Handles

A set of portable start handles was used to recreate the start handles on the luge track start ramp (Figure 3-2). The handles were made of solid steel with a frame that had spikes on the bottom to prevent sliding of the frame over the ice surface. Additionally, two pairs of 20 kg weights were used to prevent the portable handles from lifting off the ice when the athlete performed the pull start.

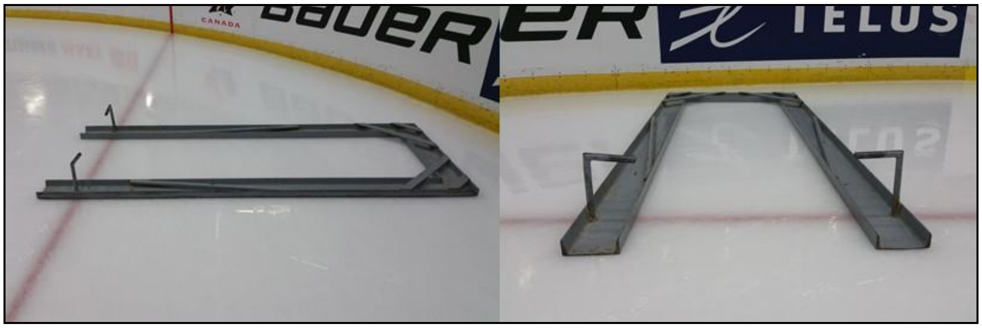


Figure 3-2. Luge portable handles side and front view. Dimensions: 203 cm (L) x 101 cm (W).

3.2.2.3 Brower timing lights

A set of Brower timing lights (three gates) was utilized to obtain time data from each trial. This timing system provides time data with the resolution of 0.01 seconds. Timing lights were located on top of a piece of foam with the same dimension as the timing light to avoid direct contact with the ice. . In some of the data collection sessions, the ice surface was still wet due to the maintenance performed on the ice rink which could have affected the integrity of the timing lights. The data obtained from the lights was displayed on a wireless handheld unit and stored on board of the handheld unit.

3.2.2.4 Motion Capture system

To evaluate the velocity output obtained from the accelerometer, an eight camera motion capture system was used (Motion Analysis Inc.; Santa Rosa, CA, USA). The motion capture system was composed of eight Raptor E high-speed cameras. 19 mm reflective markers were placed on the luge sled (Figure 3-3). The markers were screwed to a 1-inch x 1-inch piece of Velcro to easily attach them to the sled without affecting the integrity and aspect of the athlete’s luge sled. Data were collected using the software provided by the manufacturer (Cortex 3.0, Motion Analysis Inc.; Santa Rosa, CA, USA).

Figure 3-3. Reflective markers attached to the luge sled, two markers at the front and two markers at the back to ensure tracking of the markers across the volume.

3.2.3 Procedure

3.2.3.1 Location and ethics approval

Data collection sessions took place during the month of September 2014 in the ice hockey arenas located at Canada Olympic Park (Calgary, Alberta).

The study was approved by The Conjoint Health Research Ethics Board of the University of Calgary (Study name: Kinematic and kinetic factors related with bobsleigh and luge start performance times of elite bobsleigh and luge athletes, Study ID: REB13-0574). All participants read and signed a written consent from (Appendix A).

3.2.3.2 Data Collection

Prior to setting the motion capture cameras, the luge portable steel handles were set on top of the blue line of the ice rink. The position of the handles was directly over the inner portion of the blue line (Figure 3-4). From the position of the handles, plastic pylons and Bower timing lights were set up at 1.5 meters, 3.5 meters and 10.5 meters from the handles. In general, these timing light positions were chosen knowing that luge athletes perform the 1st paddle before the 3.5 metre mark and the 2nd, 3rd and 4th paddles prior to the 10 metre mark with respect to the start handles. The pylons also provided a visual aid to aim and more properly calibrate the motion analysis system in reference to the desired capture volume. Timing light data provided additional individual start performance information.

The motion analysis system was located on the ice using the respective tripods supplied by the manufacturer (Figure 3-4).

Figure 3-4. Motion analysis system and timing system layout on ice rink

The capture volume had XYZ dimensions of 13 meters (+ 5 meters, - 8 meters) in the X axis (anterior-posterior), 2 meters (+ 1 meters, -1 meter) in the Y axis (Medio- lateral) and 1.5 meters (+ 1.5 meters) in the Z axis (Vertical). Once the capture volume was defined, the system was calibrated and focused. Visual inspection of reflective markers along the capture volume was performed to ensure a proper calibration and capture volume dimensions.

Two wireless three-dimensional accelerometers were used to obtain acceleration data of the sled during luge starts on a flat surface. Also, a base station (WSDA- Base, Lord Microstrain; Williston, VT, USA) with wireless connectivity connected to a data collection laptop was used to trigger the accelerometers and to transfer the data wirelessly.

After some simple pilot testing, adhesive Velcro was chosen to attach the accelerometer to the underside of the luge sled (Figure 3-5). The Velcro did not affect the integrity of the sled as well as provided a good adhesive interface between the curved sled and flat accelerometer that was not possible with simple double sided tape.

The accelerometer was placed under the sled (Figure 3-5) and reflective markers on the anterior and posterior part of the sled (Figure 3-3). To ensure proper mounting of the sensor, a measuring tape was used to define the total length of the sled and the distance between the runners in order to locate the center of the luge sled. Subsequently, Velcro was adhered to the sled and measurements were taken again to safeguard that the sensor was located in the center of the sled.

Figure 3-5. Accelerometer mounted under the luge sled with adhesive Velcro.

Athletes were instructed to warm up as necessary and instructions were provided by the coach to minimize the chance of injury during data collection. Subjects were asked to perform pull starts in the same manner as they do in training. Once the athletes located themselves in position, they were asked first to do all the preparatory movements they require before any data collection was initiated. The subject would nod to inform the investigators that he/she was prepared to perform the start. Next, subjects were asked to remain steady for three seconds while the accelerometer was triggered to ensure a quiet period, which is crucial for proper estimation of velocity from accelerometers (it is necessary to know the initial velocity of the sled to perform the integration of the acceleration signal and obtain accurate results, in this case the velocity is 0 m/s). After this quiet period, the investigators communicated to the athlete to begin the start. In the meantime, accelerometer, motion capture and timing data were initiated and collected. Motion capture and accelerometer were configured to collect data for 15 seconds; the sampling rate was set at 250 Hz for the motion capture system and 1024 Hz for the accelerometer.

In between trials, subjects rested as much as they needed. Equipment, mounting of the accelerometer and reflective markers were checked during the rest period to ensure that all were still secured. Subjects completed a total of four trials.

3.3 Analysis

Motion capture data were post processed using Cortex software. Two reflective markers located on the back of the sled were tracked. The marker's xyz co-ordinate data were imported to Matlab software (Version 2014b, MathWorks; Natwick, MA, USA) for analysis. A Matlab script was written to filter, analyze and compare the velocity profiles from the motion analysis system with the data collected from the accelerometer.

Motion capture data were filtered using a 2^{nd} order recursive low-pass Butterworth filter with cut-off frequency at 15 Hz. The marker's displacement data were differentiated to obtain the continuous velocity profile. Four peaks were identified from the motion analysis continuous velocity curve as the pull, first paddle, second paddle and third paddle (Figure 3-6).

Accelerometer data were post processed in Matlab software. The acceleration data corresponding to the sled's horizontal acceleration was imported to the software and filtered using a 2^{nd} order low-pass Butterworth filter using a cut-off frequency of 15 Hz. Prior to any analysis of the data, the average of the initial 500 data points that were collected during the quiet period were removed from the acceleration signal to account for any component of the gravitational acceleration included in the horizontal channel if the mounting of the accelerometer to the curve bottom of the sled was not perfectly level. Once the offset was removed and the signal was filtered, the acceleration was integrated using the trapezoidal method to obtain a continuous velocity profile. Four peaks were identified as the pull, first paddle, second paddle and third paddle to create the velocity profile in a similar manner to the analysis of the motion capture data (Figure 3-6).

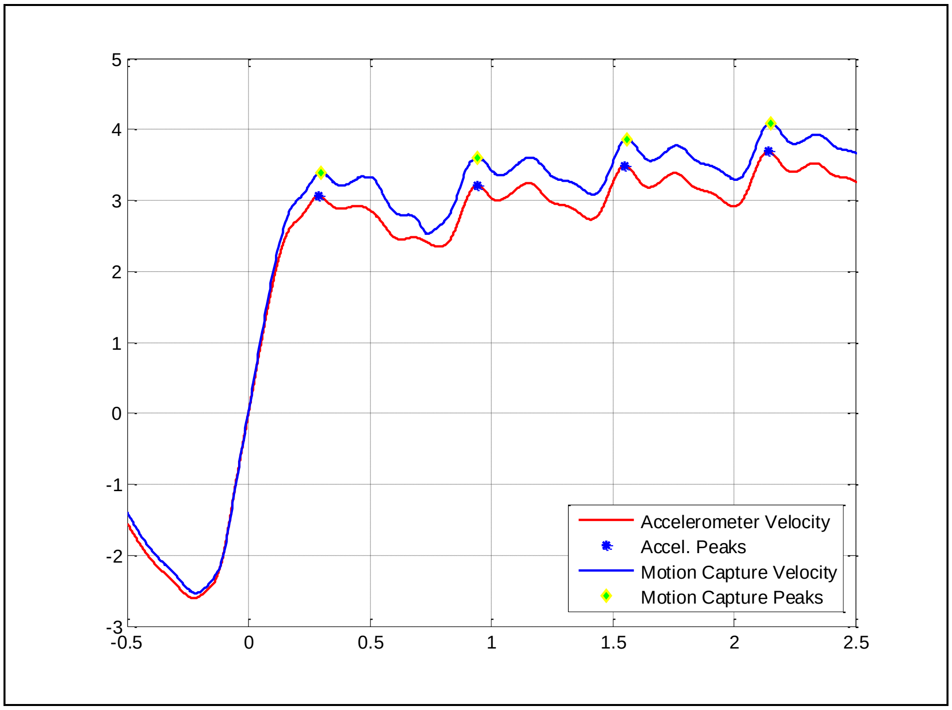


Figure 3-6. Motion Capture Velocity (m/s) profile and Accelerometer Velocity (m/s) profile. Four peaks identified as the peak velocities for the Pull, Paddle 1, Paddle 2 and Paddle 3**.**

Visual inspection of the velocity profiles was performed to assure that the peaks chosen by the program on the different profiles corresponded to the same event (Pull, first paddle, second paddle, third paddle). Synchronization of the two different velocity curves at the zero velocity point during the compression of the pull phase assured consistency of the identified events.

Statistical analysis was performed in Matlab Software. Pearson's Correlation Coefficients were calculated to compare the peaks from the motion analysis velocity curve and the velocity profile from the accelerometer curve. Descriptive statistics such as the root mean square from the two different measurements, absolute difference and percent differences were calculated to create scatter plots and Bland-Altman plots. The difference between the two methods was calculated by subtracting the velocity obtained from the accelerometer (V_{ACCEL}) from the velocity obtained with the motion capture system (V_{MOCAP}). Prior to the statistical analysis, the data were checked for outliers and normal distribution. Statistical significance level was set to $\alpha = 0.05$.

3.4 Results

V_{ACCEL} showed a strong significant correlation with V_{MOCAP} for all the events selected from the continuous velocity curve. Statistical results are summarized in Table 3-1.

Table 3-1. Summary of Statistics for the Pull, Paddle 1, Paddle 2 and Paddle 3 between the two different methods.

	Pull	**Paddle 1**	**Paddle 2**	**Paddle 3**
Mean V_{MOCAP}	3.51	3.91	4.13	4.38
Mean V_{ACCEL}	3.39	3.74	3.95	4.19
RMS Difference	0.17	0.22	0.23	0.26
RMS Percentage Difference	4.88%	5.84%	5.67%	5.96%
Person's Correlation	0.96	0.93	0.92	0.91
P-value	0.00	0.00	0.00	0.00

Figure 3-7, shows the linear increasing tendency of the velocity estimated with the accelerometer compared to V_{MOCAP}.

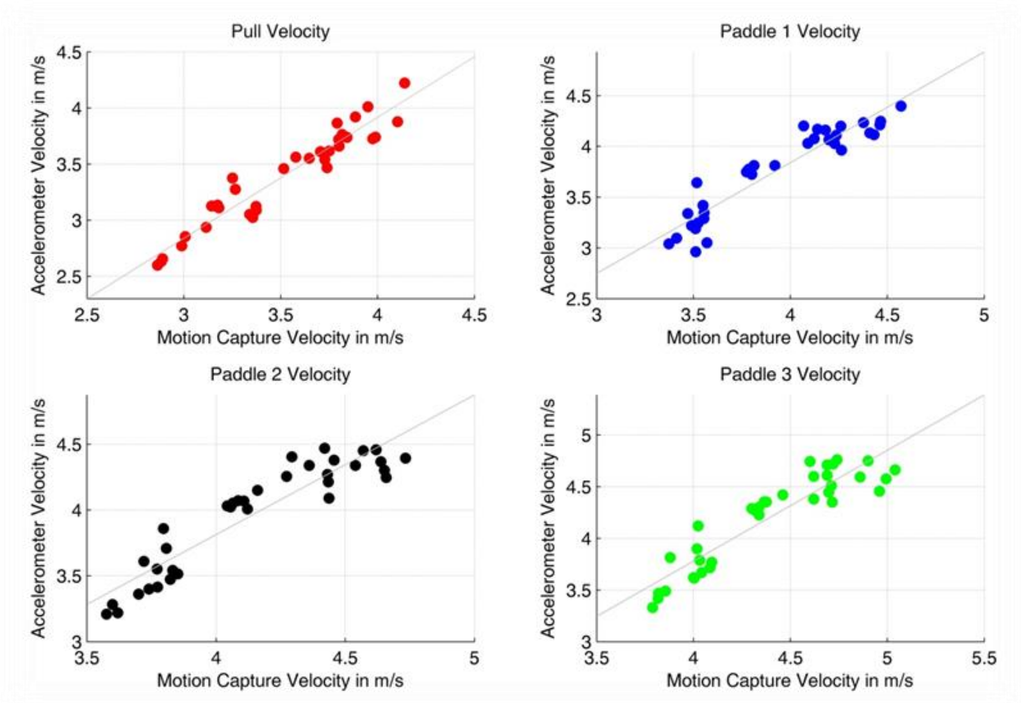


Figure 3-7. Scatter plots for the velocity events between V_{MOCAP} and V_{ACCEL}. A least-squares line was fitted to the data to demonstrate the relationship between the two variables.

Table 3-2 displays the average percent difference and standard deviation of the selected events for each of the subjects (* denotes subjects who participated twice in the data collection).

Table 3-2. Relative difference of the velocity between the MoCap and the accelerometer.

Subject		**1**	**2**	**3**	**4**	**1***	**5**	**6**	**3***	**7**	**8**	**9**
Pull	Mean	7.22	8.57	1.52	4.58	7.46	-0.64	0.62	-1.46	0.96	6.00	2.61
	SD	*1.47*	*1.25*	*1.08*	*1.86*	*2.14*	*3.01*	*2.24*	*0.55*	*0.37*	*0.43*	*1.15*
P1	Mean	12.62	8.23	1.65	4.46	8.33	1.25	-0.23	0.39	0.30	6.33	3.97
	SD	*4.27*	*0.88*	*1.25*	*1.94*	*2.16*	*4.22*	*2.67*	*1.07*	*0.30*	*0.78*	*0.84*
P2	Mean	9.61	8.72	1.09	4.54	8.38	1.27	-0.66	0.64	0.67	7.82	4.57
	SD	*1.22*	*1.01*	*1.43*	*2.14*	*2.31*	*2.57*	*1.69*	*1.86*	*0.31*	*0.90*	*1.19*
P3	Mean	10.27	8.96	1.04	4.77	8.63	0.76	-0.60	-0.28	0.80	8.67	4.59
	SD	*1.60*	*0.93*	*1.33*	*1.78*	*2.33*	*2.79*	*2.21*	*0.28*	*0.26*	*1.37*	*1.33*

The results indicate a significant amount of variability in between the subjects. Although the average percent difference for the Pull velocity is 4.88%, it can range from 0.62% to 8.57 %. Also, the results show that the difference between the two measurements is not consistent throughout the whole movement. For subject 1, the percent difference for the Pull is 7.22% while for the P1 it is 12.62%. As another example, for subject 7 the percent difference between the two methods ranged between 0.3% and 0.96%

The accelerometer seems to underestimate the sled horizontal velocity. In only 11.5% of the total velocity data points, the accelerometer overestimated the velocity, which corresponded to relatively small differences ranging from -0.3% (-0.01 m/s) to -3.8% (-0.123 m/s).

Figures 3-8 to and 3-9 represent the Bland-Altman plots for the Pull, Paddle 1, Paddle 2 and Paddle 3. Red solid lines denote the upper and lower limit for the 95% confidence of agreement intervals.

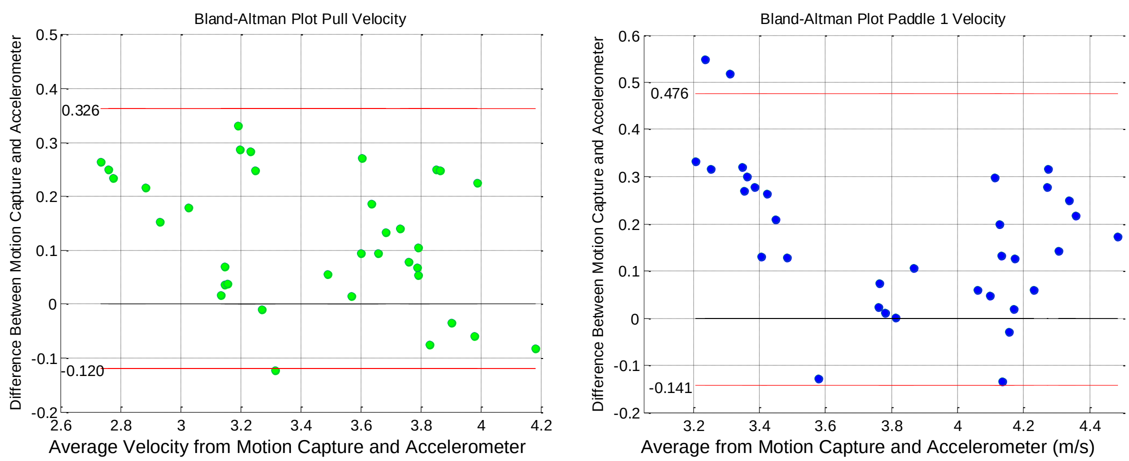


Figure 3-8. Bland-Altman Plot for Pull and Paddle 1

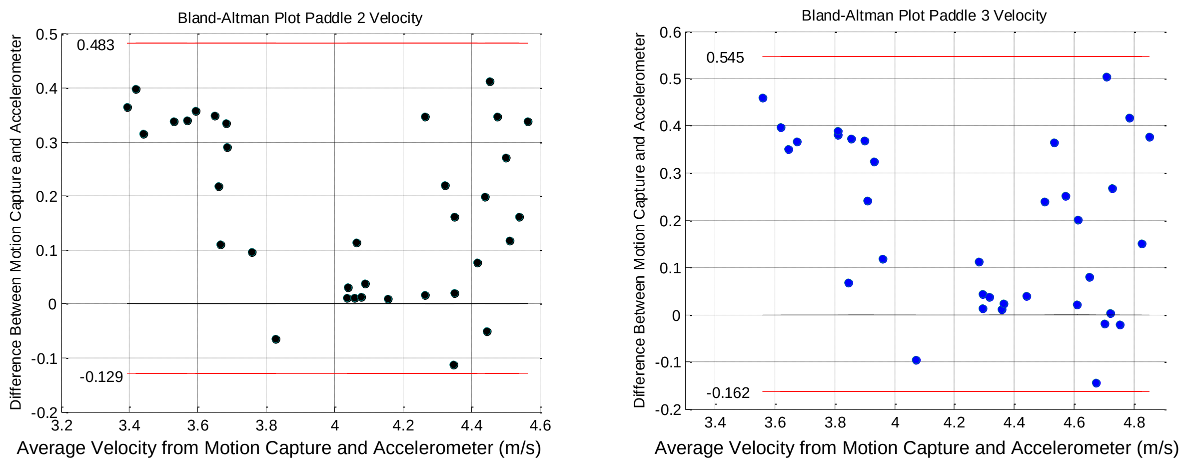


Figure 3-9. Bland-Altman Plots for Paddle 2 and Paddle 3

The plots also illustrate the under-estimation of the velocity measured with the accelerometer. Besides the under-estimation of the velocity, the Bland-Altman plots show the lack of agreement between the two measurements, as the 95% limits of agreements for the Pull ranges from 0.326 to -0.120. Also, the 95% limits of agreements increased with the consecutive paddles being of 0.476 to -0.1471, 0.483 to -0.129 and 0.545 to -0162 for Paddle 1, Paddle 2 and Paddle 3 respectively.

3.5 Discussion

The results from this section show that a three dimensional wireless accelerometer of this particular make and model, is not a valid tool to assess horizontal sled velocity during luge starts on flat ice. Figure 3-10 shows the V_{ACCCEL} curve profile can be almost identical to the reference velocity profile obtained from the motion capture. However, Figure 3-11 shows a different outcome and an underestimation the sled horizontal velocity.

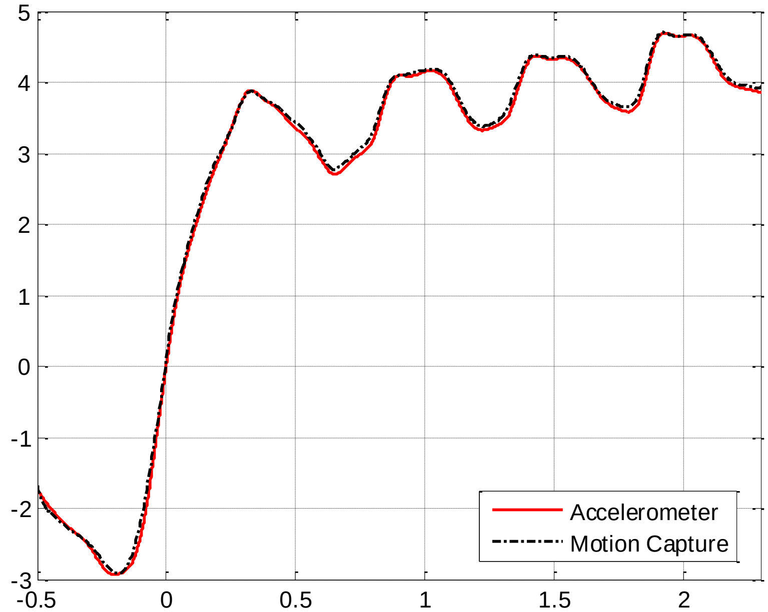


Figure 3-10. Velocity profile from Motion Capture and Accelerometer in m/s. This plot exemplifies how accurate the accelerometer can estimate sled velocity.

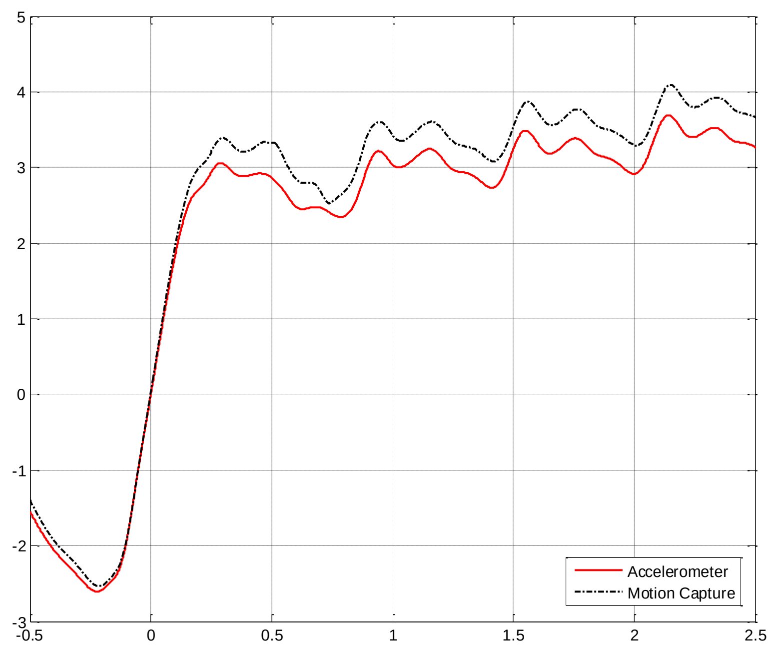


Figure 3-11. Accelerometer velocity profile versus Motion Capture velocity profile in m/s, an example of the accelerometer underestimating the sled velocity

A wireless accelerometer is a quick, practical, non-invasive tool to assess velocity, although it does not represent the true sled. There is a systematic bias in the velocity calculation that needs to be considered (the accelerometer underestimated sled velocity in almost 90% of the trials). However, there is still value in this method as other variables of interest for the coaches can be extracted (Figure 3-12). Paddle contact time and swing phase time from paddle to paddle are some of other key performance indicators that could be potentially estimated from the velocity curve. In fact, the acceleration and velocity data from each athlete start performance can be imported and analyzed as the athlete performs the technical training session.

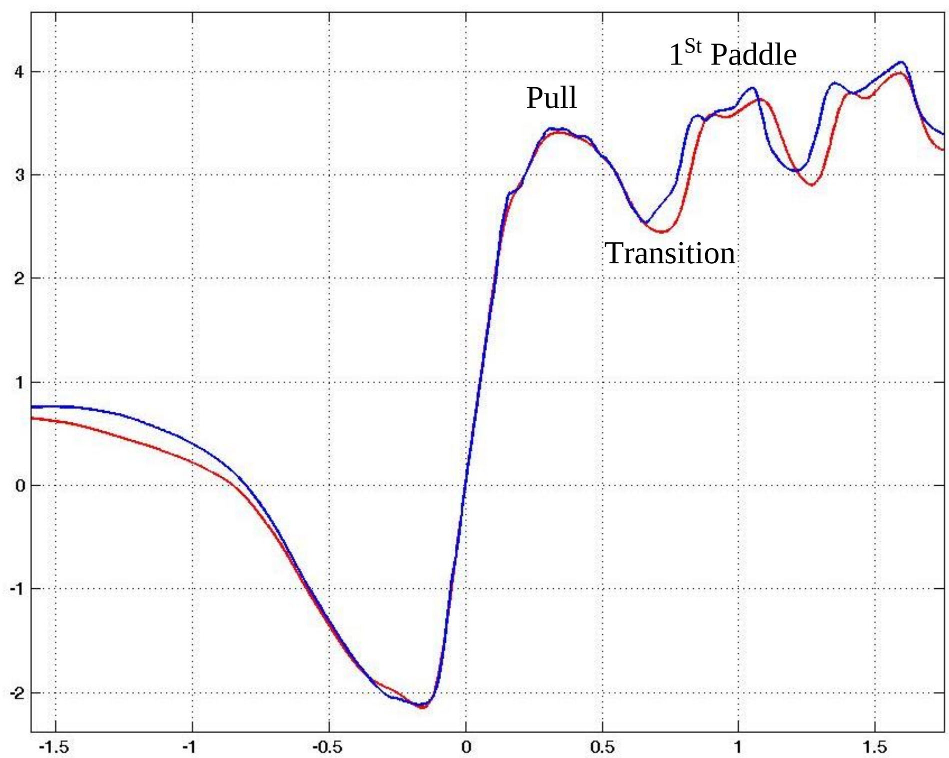


Figure 3-12. Coaches believe that the transition from the pull to the first paddle is a key factor for start performance. Blue curve (Athlete 1) shows how quicker the athlete was to reach for the first paddle after the pull compared to the red curve (Athlete 2) and its implications on the posterior velocity development.

While calculating luge sled velocity from an accelerometer signal has not been reported in the scientific literature, the results of this study seem to be in agreement with the results from previous studies where accelerometers were used to measure sled velocity in other winter sliding sports such as skeleton. Gaffney et al. (2013) found a relative error of 7.57± 4.12% between the sled velocity measured with an IMU and the reference velocity in the sport of skeleton for the measurement of start velocities. Overall, the results from the present study are more accurate than the ones from Gaffney et al. (2013), the largest RMS percent difference in this study corresponded to the second paddle (5.67 %). The smallest differences in the Gaffney study showed results of 0.176± 0.143 m/s (2.97± 2.63%), where the present study showed the smallest difference in the best trial was 0.0171± 0.015 m/s (0.43± 0.35%).

Other studies that used accelerometers and IMU application to evaluate sports performance reached similar or more accurate results than the ones reported in this project (Dadashi et al., 2012; Gaffney et al., 2015; Roberts, 2013). Still, in the previously mentioned studies, which were thoroughly discussed in the literature review, different methodologies were adopted to correct the inaccuracy of the measurement such as using an external timing device (Roberts, 2013) or knowing an objects' (athlete or sled) total displacement (Dadashi et al, 2012 ; Gaffney et al, 2015).

It is likely that the source of error in our present study is related to the mounting mechanism. In 88.5 % of the trials collected, the accelerometer underestimated the sled velocity compared to the reference. In the case when the accelerometer overestimated the velocity, it was only for very small differences corresponding to less than 0.15 m/s. The underestimation of the velocity by the accelerometer could be associated with the device's misalignment with respect to the sled. If the device is rotated around its vertical axis, part of the acceleration that had to be measured by the X-axis (anterior-posterior) would be measured by the Y-axis (medial-lateral). The higher the rotation around the Z- axis, the higher would be the “extra” acceleration collected by the Y-axis corresponding to the X-axis and the underestimation of the horizontal sled velocity would be greater (Figure 3-13).

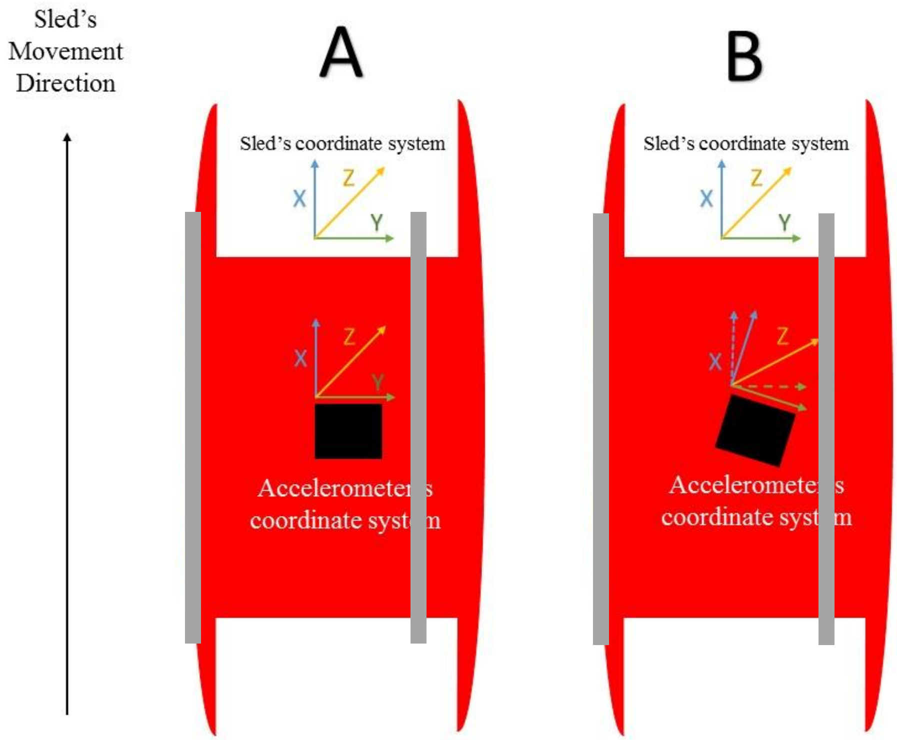


Figure 3-13. Graphical representation of how the alignment of the accelerometer with respect to the sled can affect the sensor’s accuracy. Sled A presents a correct orientation of the accelerometer with respect to the sled while in sled B the accelerometer is rotated along its vertical axis, which will result in inaccurate velocity estimations.

Future directions should investigate mounting solutions that prevent the misalignment of the device with respect to the sled. A custom made plastic mount that fits between the two runners with the accelerometer attached to the mount could be a potential solution. Additionally, synchronization of the accelerometer with a timing system fixed at short distance intervals could also assist in preventing future inaccuracies in the velocity calculations from the accelerometer.

3.6 Conclusion

A wireless 3D accelerometer with the specific characteristics used in this Chapter, resulted not be a valid tool to evaluate sled velocity during luge starts on a flat ice surface. An average RMS relative error of 5.58% was found between the velocity estimated from the accelerometer and the reference velocity. This difference is not acceptable for high performance luge athletes. The source of error could be potentially associated to the mounting of the sensor with respect of the sled.

The results from this chapter were in agreement with the previous literature were no correction factors were used to minimized the error in the velocity calculation obtained from the accelerometer.

There could still be potential value in the qualitative analysis of the velocity curve. Future research should focus in validating other key variables that could ne estimated from the accelerometer signal such as paddle contact time or paddle swing phase time.

Chapter Four: **Kinematic and Kinetic Factors Associated with Performance during the Pull Start in Elite Luge Athletes**

4.1 Introduction

The luge start is composed of two phases: the pull phase and the paddling phase. The pull phase consists of a highly explosive movement involving the trunk and upper extremity extensor musculature. The goal is to achieve the maximal sled velocity during the pull phase and continue to develop speed with the paddles. It is important to understand the crucial role that the pull phase has on overall start performance as the initial momentum is gained through the pull.

It is unlikely that an athlete with a poor performance during the pull phase will be successful in a luge competition. In a short and steep start ramp, the pull becomes an even more critical factor on the start and as a consequence in overall race performance. Similar to the paddling phase, coaches and athletes believe in the importance of mastering the pull technique and having the required strength to maximize performance during this phase. However, key performance indicators related to how athletes achieve the best pull performance are scarce in the scientific literature.

Literature has shown the importance of maximal strength on the upper extremity muscles (Platzer et al., 2009; Crossland & Hartman, 2011). End velocity (velocity at the release of the handles) appears to be related to upper extremity strength variables relative to body mass while maximal velocity was associated with absolute upper extremity strength variables. Platzer et al. (2009) also found a relationship for body mass and stature with maximal sled velocity achieved during the pull. With the exception of a handful of case studies there is no published literature that describes the effects of biomechanical factors on start performance in luge.

As a consequence of the current state of knowledge and the importance of the pull phase in overall start performance, the aim of this chapter is to achieve a better understanding of the biomechanical factors associated with a successful pull during the luge start. The following hypotheses were tested:

1. Horizontal impulse is positively correlated with the sled horizontal velocity at the release from the handles.
2. The distance of the compression (backwards sled movement) during the pull is negatively correlated with sled velocity at the release from the handles.
3. The change in magnitude from trunk flexion at the compression to trunk extension at the release of the handles is positively correlated with sled velocity at the release of the handles.

4.2 Methods

4.2.1 Participants

A total of six luge athletes ranging from 18 to 27 years old participated in the data collection session. Each of the participants belonged to the national luge team at the time of the study. Four of the participants were female with a $M_{age} = 23.3$ and the other two were male with a $M_{age} = 23.0$.

Subjects were recruited trough the Canadian National Luge Team head coach. The head coach determined the availability of the athletes based on the competition calendar and training routine. As the Luge World Cup circuit had started at the time of the study in addition to the shortage of elite luge athletes existing in Canada, the number of subjects was limited.

4.2.1.1 Inclusions

Athlete members of the national luge team who train at Canada Olympic Park (Calgary, Alberta) and were injury free at the time of the study were included in the study.

4.2.1.2 Exclusions

Subjects who did not compete during the last calendar season (2013-2014) were not included in the study.

4.2.2 Procedure

4.2.2.1 Ethics approval

The study was approved by The Conjoint Health Research Ethics Board of the University of Calgary (Study name: Kinematic and kinetic factors related with bobsleigh and luge start performance times of elite bobsleigh and luge athletes, Study ID: REB13-0574). All participants completed an informed consent from (Appendix A).

4.2.2.2 Data Collection

Data collection took place during the month of December 2014 at the luge start training indoor facility known as "The Ice House" located at Canada Olympic Park (Calgary, Alberta). The Ice House consists of an artificially refrigerated luge start ramp utilized by luge athletes for start training. The ramp recreates similar conditions to the Calgary track start ramp (Figure 4-1)

Figure 4-1. Luge artificial start ramp for the facility known as the Ice House.

The start handles at the Ice House were instrumented with force sensors (SlimLine, Kistler Holding; Winterthur, Switzerland). The sensors measured bilateral forces (right and left independent of each other) in both the anterior-posterior (horizontal) and vertical directions. The signal from the force sensors was amplified with a charge amplifier (Type 5073A, Kistler Holding; Winterthur, Switzerland) (Figure 4-2).

Figure 4-2. Start handles with integrated piezoelectric force sensors.

An eight camera motion capture system (Motion Analysis Inc., Santa Rosa, CA, USA) was used to collect kinematic data. The cameras were set up around the start handles (the handles were located at the centre of the capture volume) to generate a capture volume with the following dimensions: 5 meters in anterior-posterior direction (+3 m, -2 m; X-axis), 2 meters in the medial-lateral direction (+1 m, -1 m; Y-axis) and 1.8 m in the vertical direction (+1.8, 0 m; Z Axis) (Figure 4-3).

Figure 4-3. Motion capture cameras set up and aimed at the start handles recreating the capture volume where the athletes perform the pull start.

4.2.2.3 Procedure

Subjects were asked to do their regular training warm up before placing reflective markers on their body to assure that they would be ready to perform maximal pulls and not injure themselves. Full body bilateral marker placement consisted of the following segments (three markers per segment with exception of the third metacarpal): one marker on the middle phalange of the third metacarpal, hand, forearm, arm, upper back, lower back, thigh and lower leg.

Additional bilateral markers were located on the following anatomical landmarks for the definition of joint centres: styloid process of the ulna and radius, media and lateral epicondyle of the humerus, acromion process of the scapulae, anterior aspect of the head of the humerus, jugular notch, spinous process of C7 vertebrae, anterior superior iliac spine, head of the femur, medial and lateral femoral epicondyle. All markers were secured to the athletes using double-sided tape and were secured with duct tape to achieve maximal adhesion and minimize the chance of falling off (Figure 4-4). Four reflective markers were attached to the back and front of the luge sled.

Figure 4-4. Subject with bilateral maker placement ready for collection of static trials.

Previous to collecting motion data, static trials were captured for the definitions of joint centre locations. The subject sat on the sled holding their upper extremities at 90 degrees of shoulder flexion and shoulder abduction, keeping the elbow joints extended and palms facing anterior. Subjects were instructed to hold still as possible during the collection of the static trial. Once the static trial was captured, the joint center markers were removed.

Subjects were asked to perform a total of three trials at maximal effort to resemble an actual start during a race (Figure 4-5). In between trials, subjects were allowed to rest as much as necessary. Kinematic and kinetic data were collected while the subject performed the pull. Motion capture sampling rate was set at 250 Hz and force was collected at 2,500 Hz with a capture duration of 10 seconds. Cortex software (Motion Analysis Inc.; Santa Rosa, California) was used to collect both motion capture and force data.

Figure 4-5. Subject in position to perform the pull start.

4.2.3 Data Analysis

Raw marker data was post processed using Cortex software (Motion Analysis Inc.; Santa Rosa, California) and exported to KinTrak software (Version 7, University of Calgary; Calgary, Alberta) along with the force data for analysis. Static trials for each subject were used for joint centre definition and application of transformation measurements to the three pull trials corresponding to each subject.

Kinetic data were filtered in KinTrak using a second order low-pass filter with a cut off frequency of 30 Hz; a second order low-pass filter with a cut off frequency of 6 Hz was applied to the kinematic data. Sled kinematic data were filtered with a second order low-pass filter, cut off frequency at 15 Hz.

The dependent variables were defined as the maximal horizontal sled velocity from the compression to the release of the start handles (V_{MAX}) and the horizontal sled velocity at the moment of the release of the handles ($V_{HANDLES}$). Sled velocity was calculated by differentiating the markers at the posterior part of the sled.

Several time markers were also identified from the velocity curve of the sled to assist in the kinematic and kinetic analysis (Figure 4-7):

- Load zero velocity (V_{LOAD}): first crossing of the 0 m/s sled velocity threshold (Phase 2 on Figure 4-6)
- Maximal compression velocity ($V_{COMP\text{-}MAX}$): maximal sled horizontal negative velocity at the compression phase.
- Compression zero velocity ($V_{COMP\text{-}ZERO}$): second crossing of the 0 m/s sled velocity threshold (Phase 3 on Figure 4-6).
- Sled maximal velocity (V_{MAX}): maximal positive sled velocity (Phase 4 on Figure 4-6).
- Sled velocity at the release of the handles (V_{END}): loss of contact with the handles based on the force signal (Phase 6 on Figure 4-6).

The compression distance ($COMP_L$) was calculated from the sled horizontal position by subtracting the sled's position at V_{LOAD} from the position at $V_{COMP\text{-}ZERO}$ (Figure 4-8)

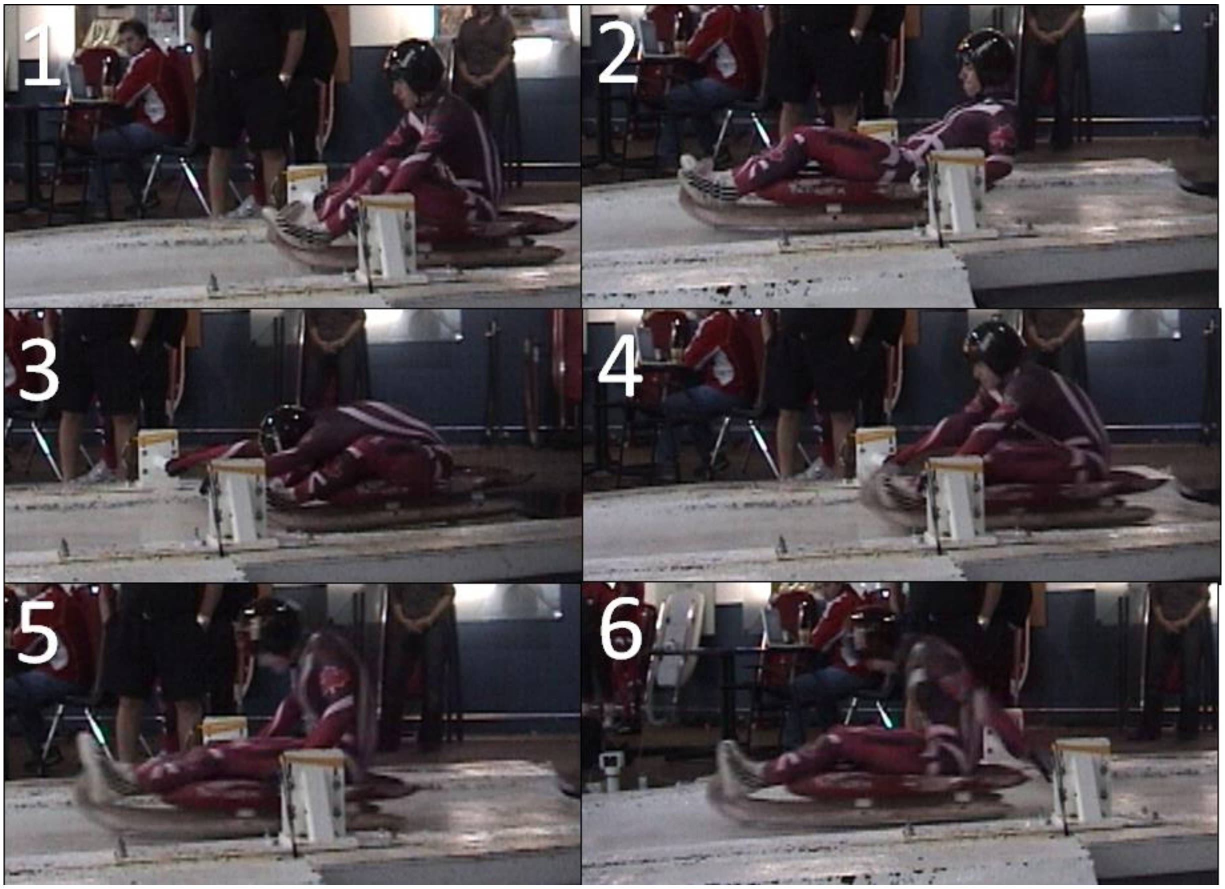


Figure 4-6. Images showing the different stages of the pull phase; **initial position** (1), initial forward movement of the sled also known as **load** (2), furthest backwards sled movement or **compression** (3), **pull 1** forwards displacement of the sled from the compression initiated by the back extension (4), **pull 2** moment where the hips cross the start handles in the sagittal plane (5) and the **release** or loss of contact with the start handles (6).

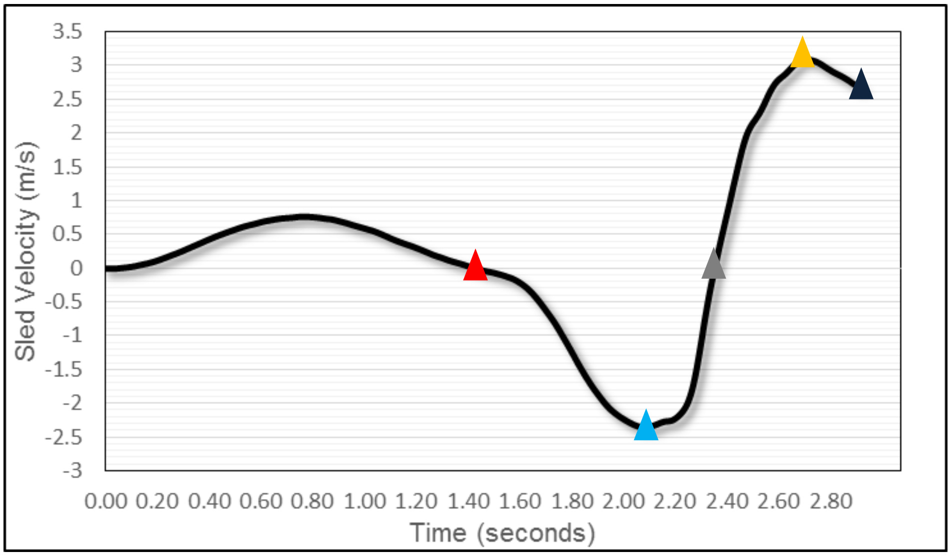


Figure 4-7. Typical sled velocity curve from the load to the release of the start handles; V_{LOAD} (red triangle), $V_{COMP\text{-}MAX}$ (light blue triangle), $V_{COMP\text{-}ZERO}$ (grey triangle), V_{MAX} (yellow triangle) and V_{END} (dark blue triangle) were extracted from the velocity curve of the sled.

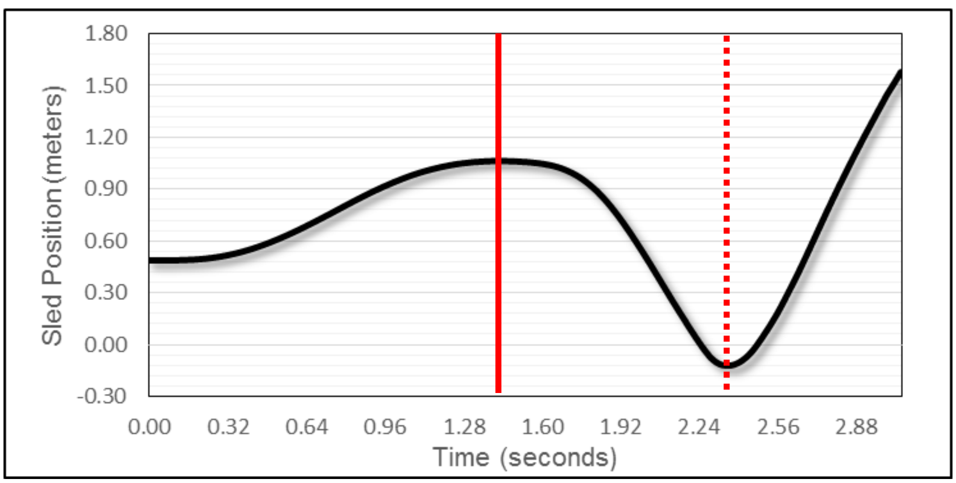


Figure 4-8. Sled position based on the sled's markers, compression distance was estimated from the sled's position at V_{LOAD} (solid red line) and the position at $V_{COMP\text{-}ZERO}$ (dashed red line.)

For the kinematic analysis, bilateral joint angles were analyzed and were defined as follows:

- Elbow joint: relative movement of the forearm segment with respect to the arm segment.
- Shoulder joint: relative movement of the arm segment with respect to the upper back.
- Upper back: relative movement of the upper back segment with respect to the laboratory.

Peak trunk flexion ($TRUNK_{PEAK}$) was defined as the maximal flexion of the upper back segment between the time markers $V_{COMP\text{-}MAX}$ and V_{MAX} (Figure 4-9). The change in magnitude of trunk extension ($\Delta TRUNK_{PEAK\text{-}MAX}$) was calculated as the variation in trunk extension from $TRUNK_{PEAK}$ to the V_{MAX} time point (Figure 4-9 solid red line to dotted red line). Also, the change in magnitude of trunk extension ($\Delta TRUNK_{PEAK\text{-}MIN}$) was studied from $TRUNK_{PEAK}$ to the minimum flexion of the trunk segment ($TRUNK_{MIN}$).

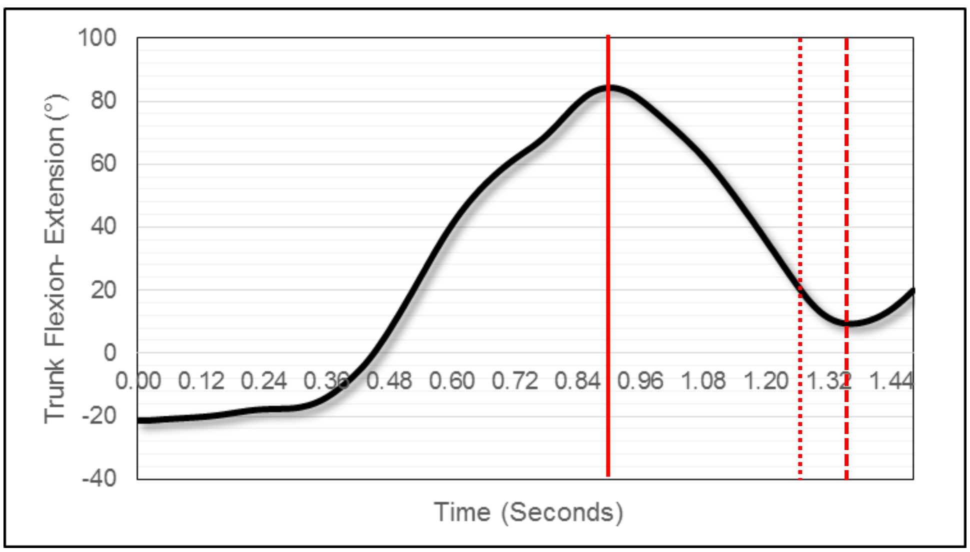


Figure 4-9. Trunk flexion-extension from V_{LOAD} to V_{END}, solid red line denotes $TRUNK_{PEAK}$; dashed red line represents $TRUNK_{MIN}$. Dotted red line shows trunk flexion-extension at V_{MAX}. Positive increasing values indicate trunk flexion and decreasing values reflect trunk extension.

The analysis of the force data included several kinetic variables (Table 4-1) between the subsequent time points. These time points are shown in Figure 4-10 below.

Table 4-1. List of kinetic variables analyzed between three different time markers. The sled's mass (23kg) was added to the mass of the subjects for the relative to body weight variables. Net forces were calculated from the left and right force sensors.

Time Marker	Variable name	Description
$V_{COMP\text{-}ZERO} - V_{END}$	N-$PF_{ZERO\text{-}END}$	Net maximal force from $V_{COMP\text{-}ZERO}$ to V_{END}
	N-$MF_{ZERO\text{-}END}$	Net average force from $V_{COMP\text{-}ZERO}$ to V_{END}
	N-$Imp_{ZERO\text{-}END}$	Net Impulse from $V_{COMP\text{-}ZERO}$ to V_{END}
	RF/$BW_{ZERO\text{-}END}$	Relative net mean force to body weight from $V_{COMP\text{-}ZERO}$ to V_{END}
	Imp/$BW_{ZERO\text{-}END}$	Relative net impulse to body weight from $V_{COMP\text{-}ZERO}$ to V_{END}
$V_{ZERO} - V_{MAX}$	N-$MF_{ZERO\text{-}MAX}$	Net average force from $V_{COMP\text{-}ZERO}$ to V_{MAX}
	N-$IMP_{ZERO\text{-}MAX}$	Net Impulse from $V_{COMP\text{-}ZERO}$ to V_{MAX}
	RF/$BW_{ZERO\text{-}MAX}$	Relative net mean force to body weight from $V_{COMP\text{-}ZERO}$ to V_{MAX}
	Imp/$BW_{ZERO\text{-}MAX}$	Relative net impulse to body weight from $V_{COMP\text{-}ZERO}$ to V_{MAX}
$V_{MAX} - V_{END}$	N-$MF_{MAX\text{-}END}$	Net average force from V_{MAX} to V_{END}
	N-$Imp_{MAX\text{-}END}$	Net Impulse from V_{MAX} to V_{END}
	RF/$BW_{MAX\text{-}END}$	Relative net mean force to body weight from V_{MAX} to V_{END}
	Imp/$BW_{MAX\text{-}END}$	Relative net impulse to body weight from V_{MAX} to V_{END}

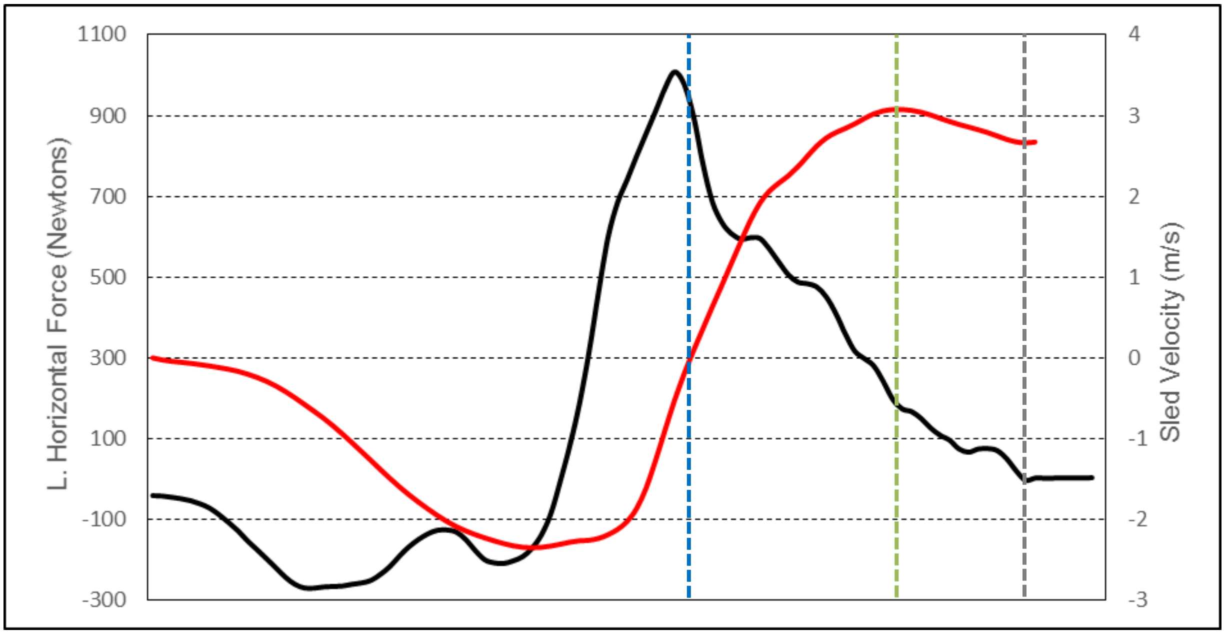


Figure 4-10. Typical anterior-posterior force trace (black solid line) and sled velocity (red solid line) profile from V_{LOAD} (zero velocity point at the load phase) to V_{END} (velocity at the release of the start handles). Blue dashed line represents $V_{COMP\text{-}ZERO}$, V_{MAX} represented by green dashed line and V_{END} by dashed grey line. These time markers from the velocity curve were used to calculate the kinetics between $V_{COMP\text{-}ZERO}$ to V_{END}, $V_{COMP\text{-}ZERO}$ to V_{MAX} and V_{MAX} to V_{END}.

The statistical analysis was performed in Matlab software (Version 2014b, MathWorks; Natwick, MA, USA). Due to the violation of the normality assumption and small sample size (n=6), non-parametric statistics were chosen for analysis. Normality was evaluated with normal probability distribution plots.

Spearman Rank Correlation was used to study the linear relationship between the independent and dependent variable. For the kinetic analysis of the variables contemplated between V_{ZERO} and V_{MAX}, the dependent variable was V_{MAX} (maximal horizontal sled velocity). For the variables between V_{ZERO} - V_{END} and V_{MAX} – V_{END}, velocity at the release of the handles

(V_{END}) was chosen as the outcome variable. The analysis was performed for the total number of subjects and stratified into males and females.

4.3 Results

The outcome variable for this chapter depended on the part of the movement that was being analyzed. In an actual competition setting, the velocity at the release from the handle (V_{END}) should be considered as the performance criteria of the pull phase. However, to understand how luge athletes achieve this end velocity, the maximal velocity (V_{MAX}) reached during the pull was also taken into consideration (Figure 4-11). A positive and significantly moderate correlation was found between V_{END} and V_{MAX} (ρ = 0.54, p-value = 0.019) for all the athletes (Figure 4-11). This relationship increased for the male subjects (ρ = 0.714, p-value = 0.136) although not being statistically significant. The female subjects presented a non-significant moderate negative correlation of -0.560 (p-value = 0.055) (Figure 4-12).

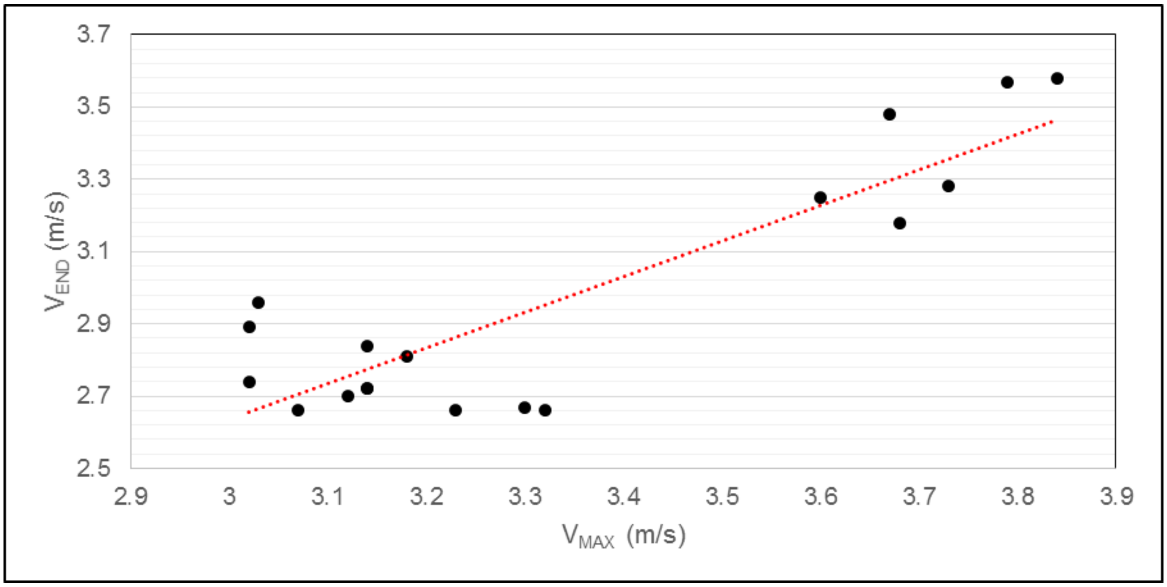


Figure 4-11. Scatter plot for V_{END} vs V_{MAX}, when both males and females are considered in the analysis these variables show a positive relationship ($\rho = 0.54$, p-value = 0.019)

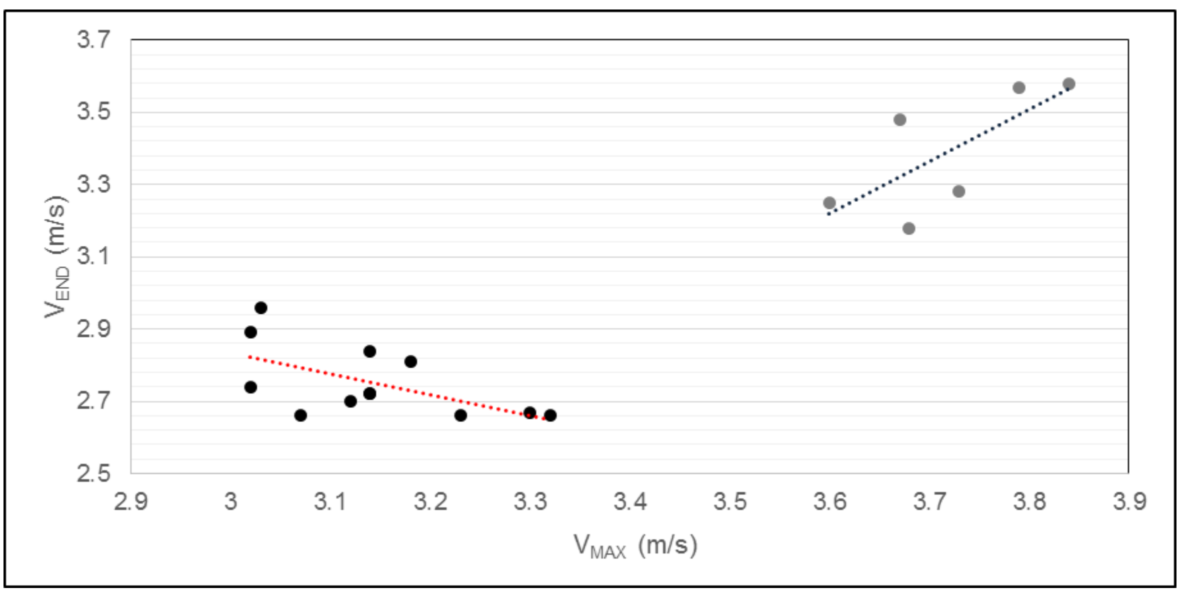


Figure 4-12. Scatter plot for male (grey dots) and female (black dots) subjects, plot illustrate the inverse relationship based on gender between V_{MAX} and V_{END}.

4.3.1 Compression distance and its relationship with V_{MAX} and V_{END}

Results from the correlation analysis between $COMP_L$ and the velocity variables are summarized in Table 4-2. $COMP_L$ showed a high negative significant correlation for V_{MAX} when all subjects (Figure 4-13) and female subjects (Figure 4-14) were considered, however it did not seem to maintain this association with V_{END} with the exception of the male subjects (Table 4-3). Mean statistics for $COMP_L$ and the outcome variable are presented in Table 4-3.

Table 4-2. Summary of Spearman Rank Correlation Coefficients for $COMP_{L;}$ all subjects (♀ & ♂), male (♂) and female subjects (♀). Results in bold and with an asterisk represent statistically significant results.

Group	rho	V_{MAX}	V_{END}
♀ & ♂	ρ	**-0.753***	-0.293
(n=6)	p-value	**0.000***	0.238
♀	ρ	**-0.780***	0.455
(n=4)	p-value	**0.003***	0.136
♂	ρ	-0.783	**-0.985***
(n=2)	p-value	0.077	**0.005***

Table 4-3. Mean statistics for $COMP_L$ and the outcome variables for the three trials completed by the subjects.

Subject	Gender	$COMP_L$ (m)	V_{MAX} (m/s)	V_{END} (m/s)
1	♀	-1.20	3.13	2.80
2	♀	-1.11	3.13	2.71
3	♀	-1.00	3.02	2.86
4	♀	-1.21	3.28	2.66
5	♂	-1.17	3.67	3.24
6	♂	-1.47	3.77	3.54

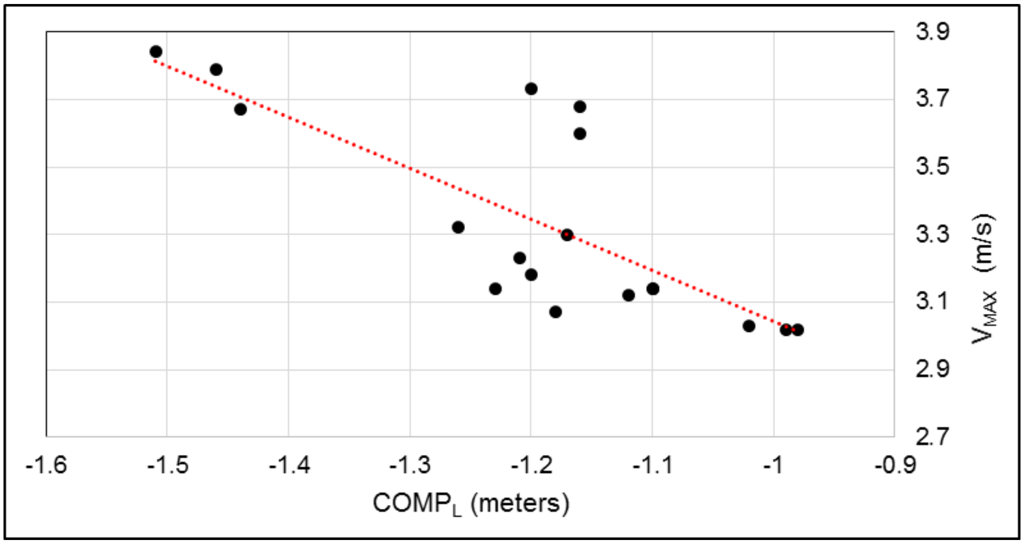


Figure 4-13. COMP$_L$ plotted against V_{MAX} for all subjects (ρ= -0.753, p-value =0.000)

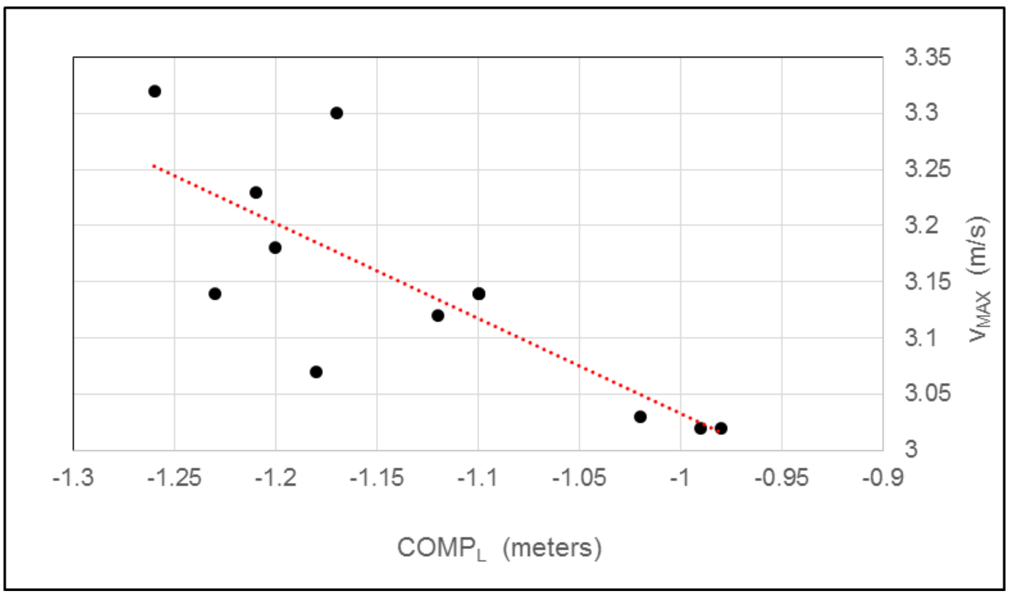


Figure 4-14. COMP$_L$ plotted against V_{MAX} for ♀ subjects (ρ = -0.780, p-value 0.000)

4.3.2 Variation in Magnitude of trunk extension and pull performance.

Spearman rank correlation summarizing the results from the statistical analysis are displayed in Table 4-4. For the variable $\Delta TRUNK_{PEAK-MAX}$, V_{MAX} was the outcome variable whereas in the case of $\Delta TRUNK_{PEAK-MIN}$, V_{END} was considered the outcome.

Table 4-4. Summary of Spearman Rank correlation coefficients for $\Delta TRUNK_{PEAK-MAX}$ and $TRUNK_{PEAK-MIN}$. Results in bold and with an asterisk represent statistically significant results.

Gender	rho	$\Delta TRUNK_{PEAK-MAX}$	$\Delta TRUNK_{PEAK-MIN}$
♀ & ♂	ρ	-0.37	**-0.61***
(n=6)	p-value	0.1302	**0.009***
♀	ρ	0.412	-0.23
(n=4)	p-value	0.182	0.46
♂	ρ	0.314	0.4
(n=2)	p-value	0.563	0.516

$TRUNK_{PEAK-MIN}$ presented a moderate negative correlation with V_{END} (Figure 4-15) when all the subjects when taken into the consideration. The remainder of the statistical test showed weak correlations with the dependent variables without statistical significance.

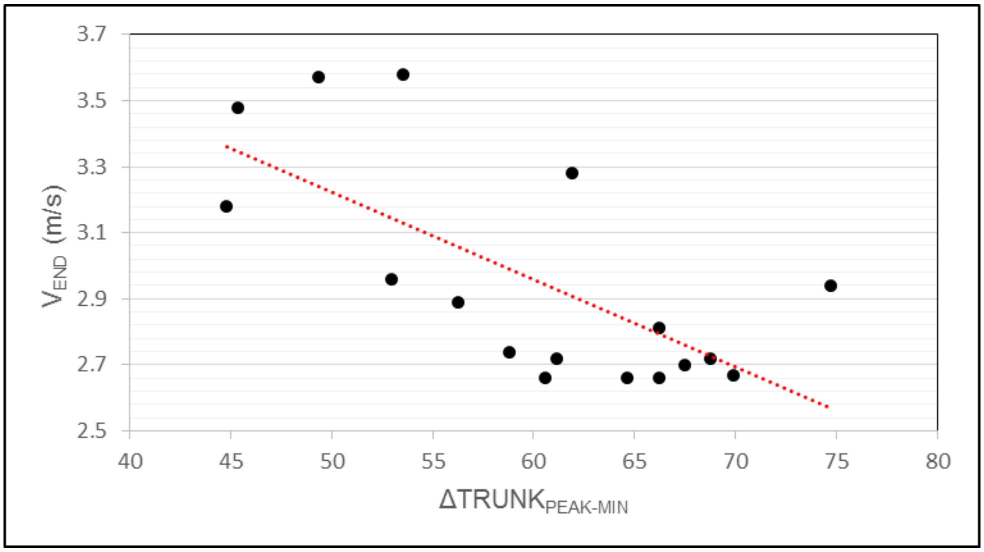


Figure 4-15. V_{END} versus $\Delta TRUNK_{PEAK\text{-}MIN}$ for all athletes displays an negative relationship among the two variables (ρ = -0.610, p-value 0.009)

4.3.3 Kinetic analysis from $V_{COMP\text{-}ZERO}$ to V_{END}

Moderate to high correlations were found for the kinetic analysis from $V_{COMP\text{-}ZERO}$ to V_{END} for all athletes. The highest correlation with V_{END} corresponded to the $RF/BW_{ZERO\text{-}END}$ (Figure 4-16). Summary of the statistical results is shown in Table 4-5.

Male subjects showed very high significant correlation for $N\text{-}Imp_{ZERO\text{-}END}$, $N\text{-}MF_{ZERO\text{-}END}$ and $RF/BW_{ZERO\text{-}END}$ (Figure 4-18 & 4-19). On the contrary, for the female athletes none of the kinetic variables presented statistical significance and a strong correlation with V_{END} (Figures 4-20 & 4-21). Mean values for V_{END} and $RF/BW_{ZERO\text{-}END}$ are displayed on Figure 4-17.

Table 4-5. Correlation coefficients for the kinetic variables from $V_{COMP\text{-}ZERO}$ to $V_{END.}$ Results in bold and with an asterisk represent statistically significant results.

Gender	rho	N-PF$_{ZERO\text{-}END}$	N-Imp$_{ZERO\text{-}END}$	N-MF$_{ZERO\text{-}END}$	Imp/BW$_{ZERO\text{-}END}$	RF/BW$_{ZERO\text{-}END}$
⚥	ρ	**0.685***	**0.589***	**0.699***	**0.555***	**0.824***
(n=6)	p-value	**0.0017***	**0.010***	**0.001***	**0.017***	**0.000***
♀	ρ	0.088	-0.395	-0.018	0.049	0.470
(n=4)	p-value	0.785	0.204	0.957	0.879	0.123
♂	ρ	0.82	**0.942***	**0.942***	0.428	**0.942***
(n=2)	p-value	0.058	**0.0167***	**0.0167***	0.419	**0.0167***

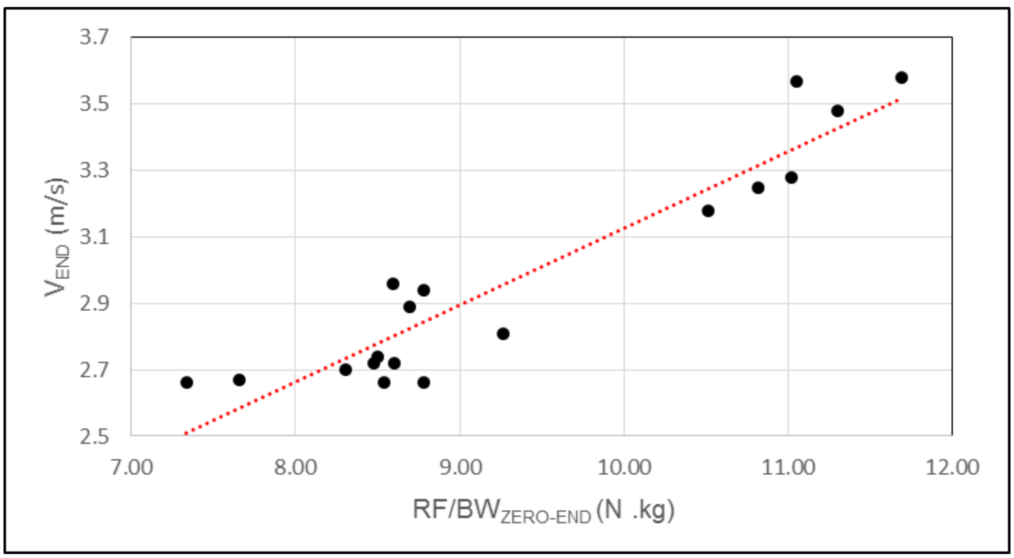


Figure 4-16. Scatter plot illustrating the relation between $RF/BW_{ZERO\text{-}END}$ and V_{END} (all subjects) (rho = 0.824, p-value= 0.00)

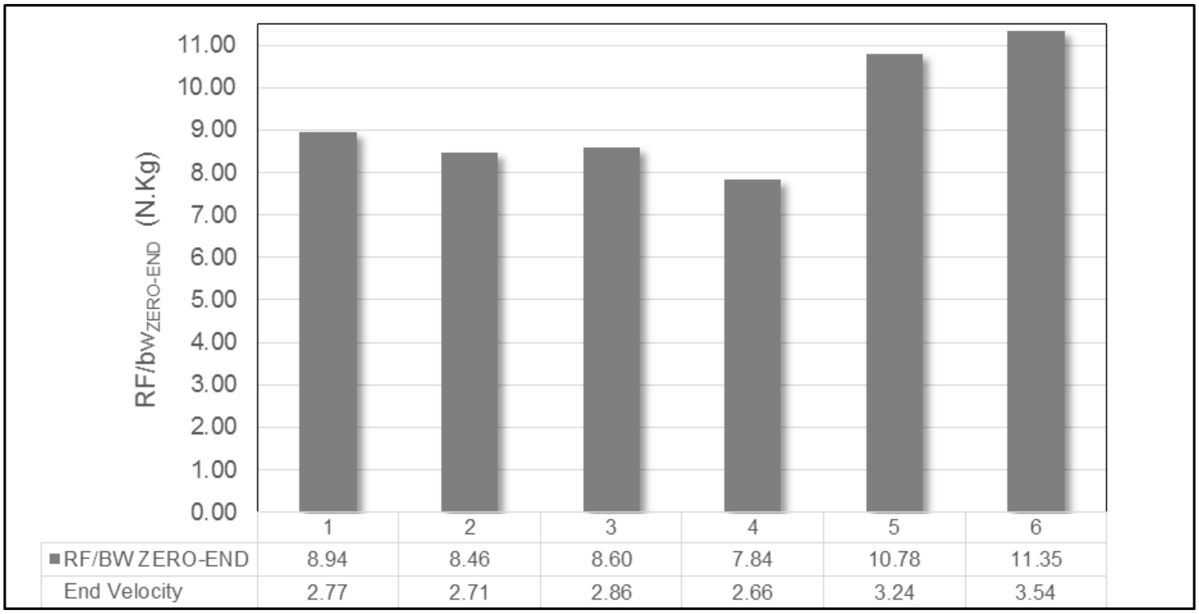


Figure 4-17. Mean RF/BW$_{ZERO\text{-}END}$ for subjects 1 to 6, data table shows mean values for V$_{END}$ (m/s).

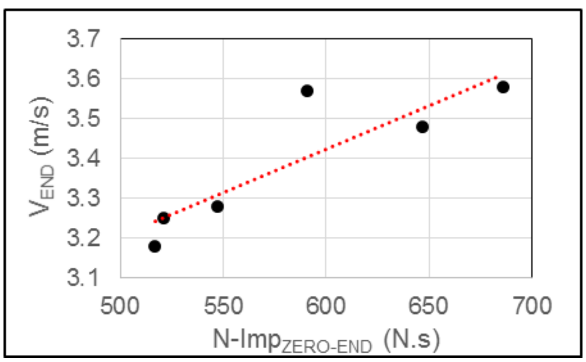


Figure 4-18. N-Imp$_{ZERO\text{-}END}$ vs. V$_{END}$ (♂).

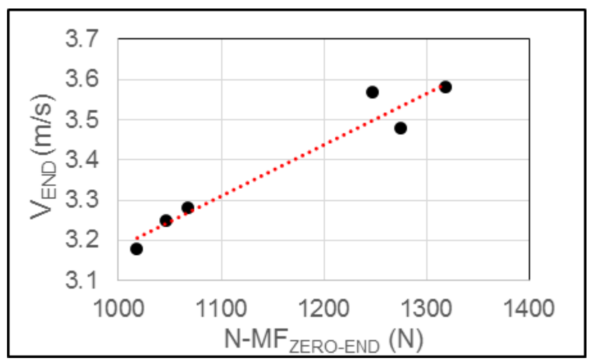


Figure 4-19. N-MF$_{ZERO\text{-}END}$ vs. V$_{END}$ (♂).

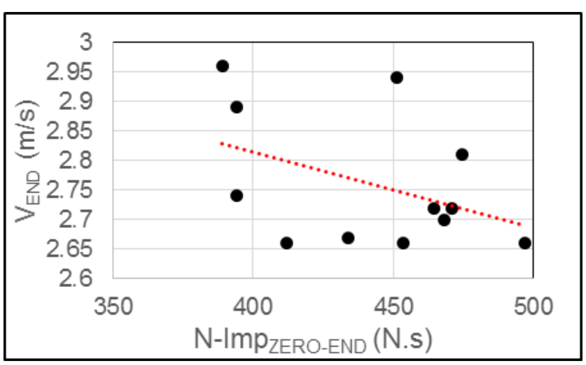


Figure 4-20. N-Imp$_{ZERO\text{-}END}$ vs. V$_{END}$ (♀).

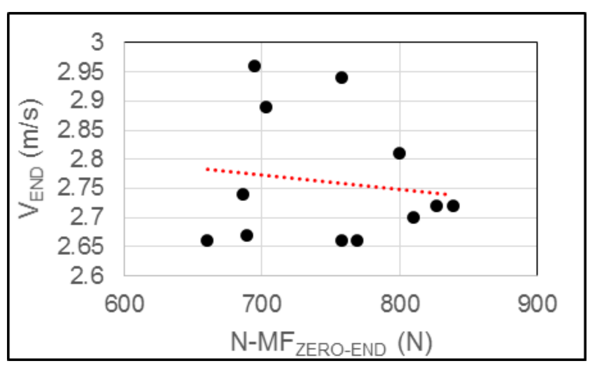


Figure 4-21. N-MF$_{ZERO\text{-}END}$ vs. V$_{END}$ (♀).

4.3.4 Results from kinetic analysis from $V_{COMP\text{-}ZERO}$ to V_{MAX}

Statistical results indicated high correlation coefficients for N-$Imp_{ZERO\text{-}MAX}$, N-$MF_{ZERO\text{-}MAX}$ and Imp/$BW_{ZERO\text{-}MAX}$ (Table 4-6, Figure 4-22). However, these coefficients significantly dropped when the data was stratified into male and female groups (Figure 4-23). All the statistical tests were statistically insignificant, except for N-$Imp_{ZERO\text{-}MAX}$ which remained high with a correlation coefficient for the male subjects (Figure 4-24)

Table 4-6. Summary of Spearman Rank Correlation coefficients for the kinetic variables from $V_{COMO\text{-}ZERO}$ to V_{MAX}. Results in bold and with an asterisk represent statistically significant results.

Gender	**rho**	**N-Imp$_{ZERO\text{-}MAX}$**	**N-MF$_{ZERO\text{-}MAX}$**	**Imp/BW$_{ZERO\text{-}MAX}$**	**RF/BW$_{ZERO\text{-}MAX}$**
⚥	ρ	**0.817***	**0.778***	**0.847***	**0.556***
(n=6)	p-value	**0.000***	**0.000***	**0.000***	**0.017***
♀	ρ	0.407	0.344	0.492	-0.375
(n=4)	p-value	0.189	0.274	0.104	0.229
♂	ρ	0.771	0.200	**0.886***	-0.086
(n=2)	p-value	0.103	0.714	**0.033***	0.919

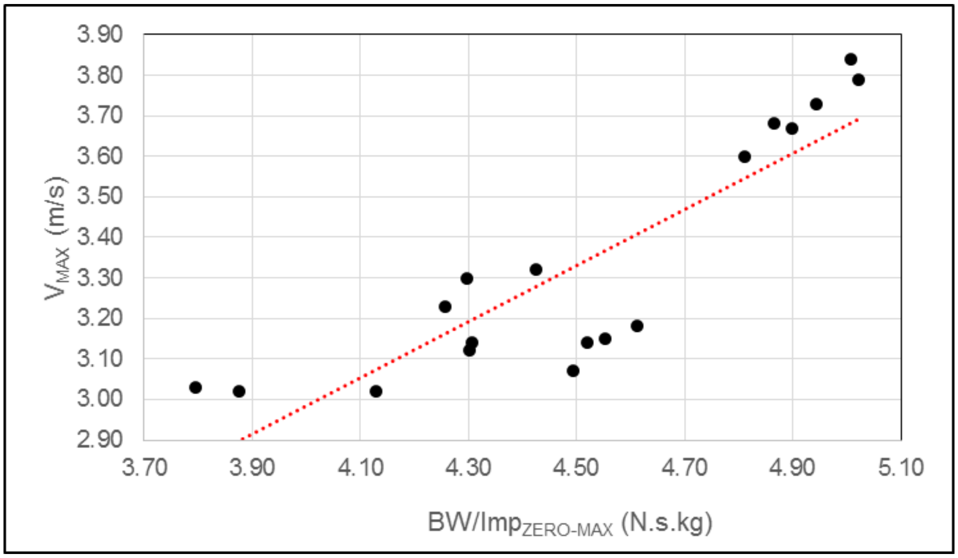


Figure 4-22. Scatter plot for V_{MAX} and $Imp/BW_{ZERO-MAX}$ (all subjects); ρ = 0.847, p-value = 0.00.

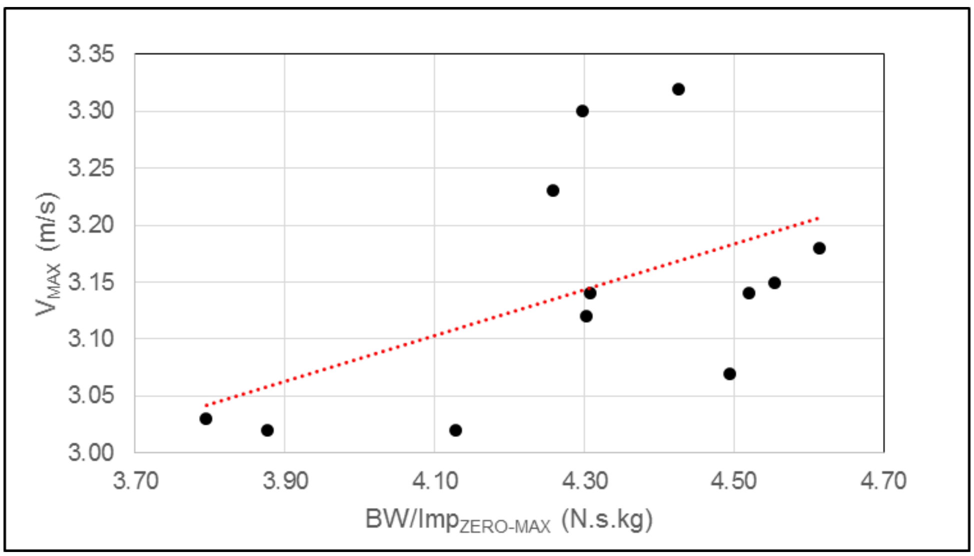


Figure 4-23. $Imp/BW_{ZERO-MAX}$ (N.s.kg) versus V_{MAX} for female subjects (ρ = 0.492, p-value = 0.104)

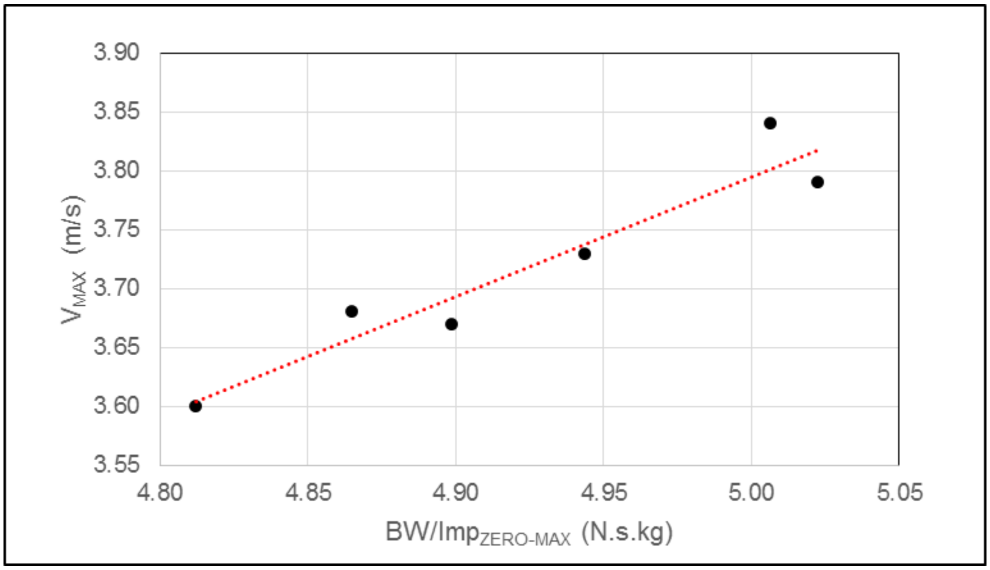


Figure 4-24. $Imp/BW_{ZERO-MAX}$ (N.s.kg) versus V_{MAX} for male subjects ($\rho = 0.886$, p-value = 0.033).

4.3.5 Results from kinetic analysis from V_{MAX} to V_{END}

The statistical analysis showed high to very high correlation coefficients for $N\text{-}MF_{MAX\text{-}END}$ ($r_s = 0.857$) and $RF/BW_{MAX\text{-}END}$ ($r_s = 0.777$) and moderate correlation coefficients for $N\text{-}Imp_{MAX\text{-}END}$ ($r_s = 0.620$) and $Imp/BW_{MAX\text{-}END}$ ($r_s = 0.629$) when all the athletes were taken into consideration (Figure 4-25). Correlation coefficients remained high in the case of the female subjects for $N\text{-}MF_{MAX\text{-}EX}$ and $RF/BW_{MAX\text{-}END}$ (Figure 4-26). Correlation coefficients were also high for all the kinetic variables in the case of the males but statistically insignificant (Table 4-7). Average values for $RF/BW_{MAX\text{-}END}$ and V_{END} shown in figure 4-27.

Table 4-7. Spearman Rank correlation coefficients for kinetic variables from V_{MAX} to V_{END}.

Results in bold and with an asterisk represent statistically significant results.

Gender	rho	N-Imp$_{MAX-END}$	N-MF$_{MAX-END}$	Imp/BW$_{MAX-END}$	RF/BW$_{MAX-END}$
⚥	ρ	**0.62***	**0.857***	**0.629***	**0.777***
(n=6)	p-value	**0.005***	**0.000***	**0.000***	**0.000***
♀	ρ	0.338	**0.754***	0.455	**0.805***
(n=4)	p-value	0.281	**0.004***	0.137	**0.001***
♂	ρ	0.771	0.714	0.771	0.714
(n=2)	p-value	0.103	0.136	0.103	0.136

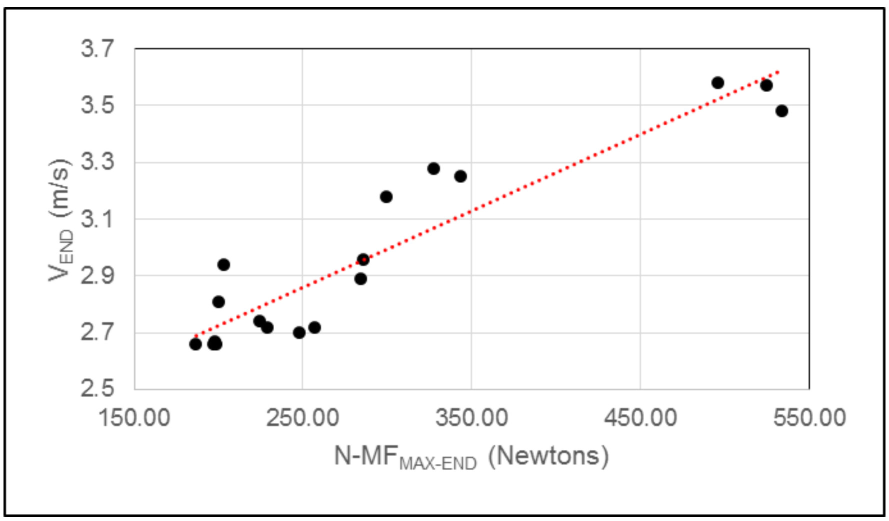


Figure 4-25. Scatter plot for N-MF$_{MAX-END}$ versus V_{END} (all subjects); $\rho = 0.857$, p-value = 0.000.

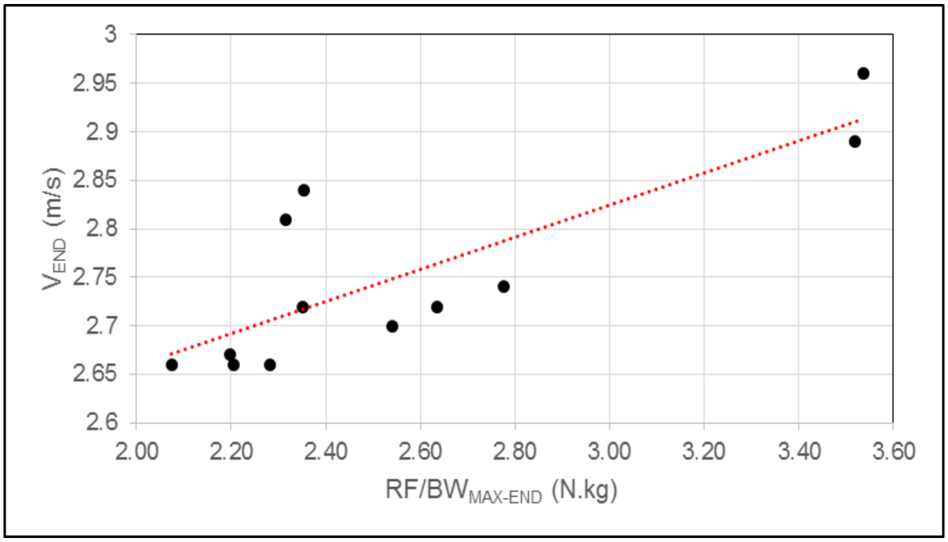
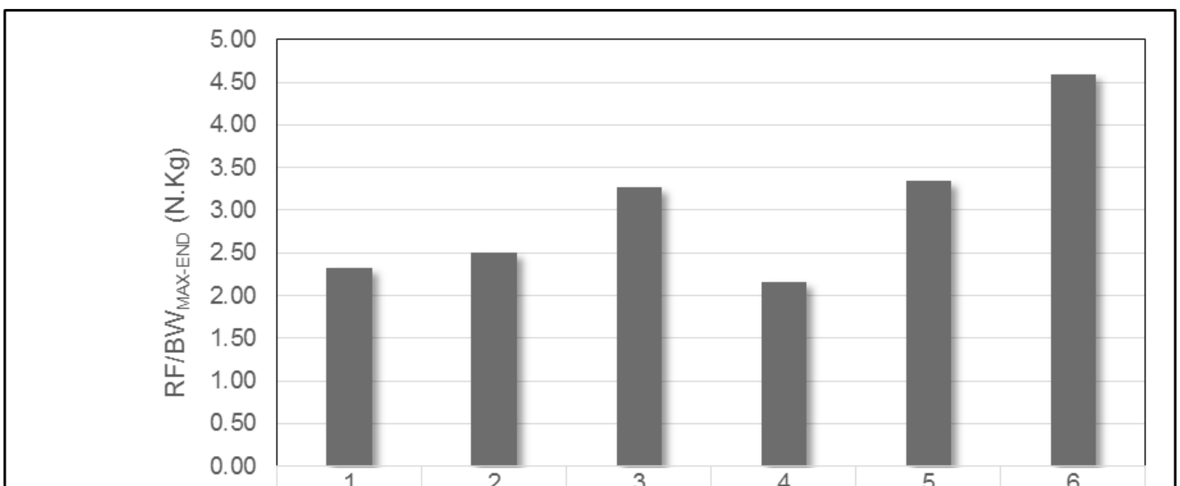


Figure 4-26. Scatter plot for $RF/BW_{MAX-END}$ and V_{END} (female subjects); $\rho = 0.805$, p-value = 0.003.



	1	2	3	4	5	6
RF/BW MAX-END	2.32	2.51	3.28	2.16	3.34	4.59
End Velocity	2.77	2.71	2.86	2.66	3.24	3.54

Figure 4-27. Mean $RF/BW_{MAX-END}$ and mean subjects 1-6. Data tables shows average V_{END} (m/s)

4.3.6 Additional results

Additional data analysis incorporated the anthropometric variable body mass and its relation with the outcome variable V_{MAX} and V_{END} (Table 4-8).

Table 4-8. Average values for the kinetic variables between $V_{COMP\text{-}ZERO}$ to V_{END}, $COMP_L$ and outcome variables. The variable mass (Kg) includes the weight of the sled (23 Kg).

Subject	**Gender**	**Mass (Kg)**	**N-Imp$_{ZERO\text{-}END}$ (N.s)**	**N-MF$_{ZERO\text{-}END}$ (N)**	**Imp/BW$_{ZERO\text{-}END}$ (N.s.Kg)**	**RF/BW$_{ZERO\text{-}END}$ (N.Kg)**	**V_{MAX} (m/s)**	**V_{END} (m/s)**
1	♀	86.30	459.74	771.68	5.33	8.94	3.13	2.77
2	♀	97.50	467.98	824.93	4.80	8.46	3.13	2.71
3	♀	80.80	392.38	694.48	4.86	8.60	3.02	2.86
4	♀	90.00	447.67	705.96	4.97	7.84	3.28	2.66
5	♂	96.80	528.33	1043.81	5.46	10.78	3.67	3.24
6	♂	112.80	641.23	1279.96	5.68	11.35	3.77	3.54

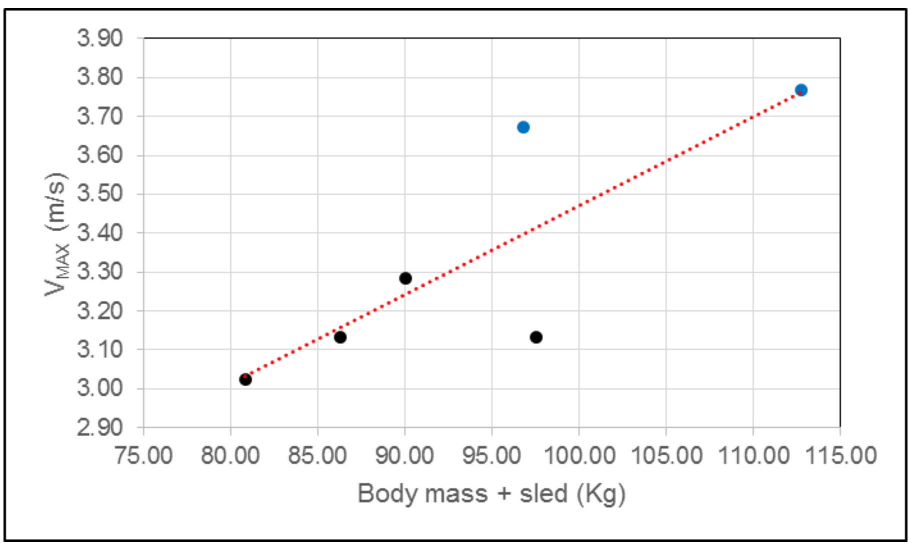


Figure 4-28. Scatter plot illustrating the relationship between body mass and average V_{MAX}, black dots represent female subjects and blue dots male subjects.

Body mass appears to have a positive relationship with V_{MAX} when all the subjects are considered (Figure 4-28). The same association can be observed in the case of the female subjects (Figure 4-29). However, when looking at females, body mass has an opposite relationship with V_{END} (Figure 4-30).

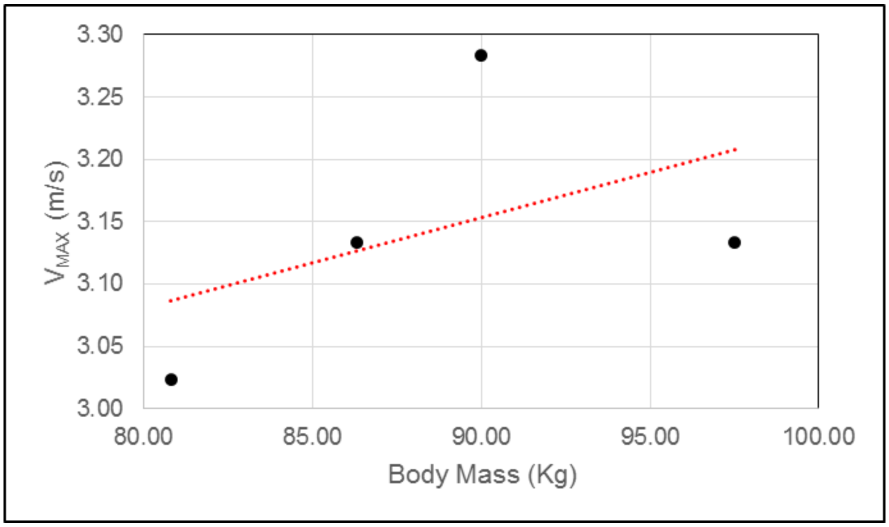


Figure 4-29. V_{MAX} versus body mass for the female subjects

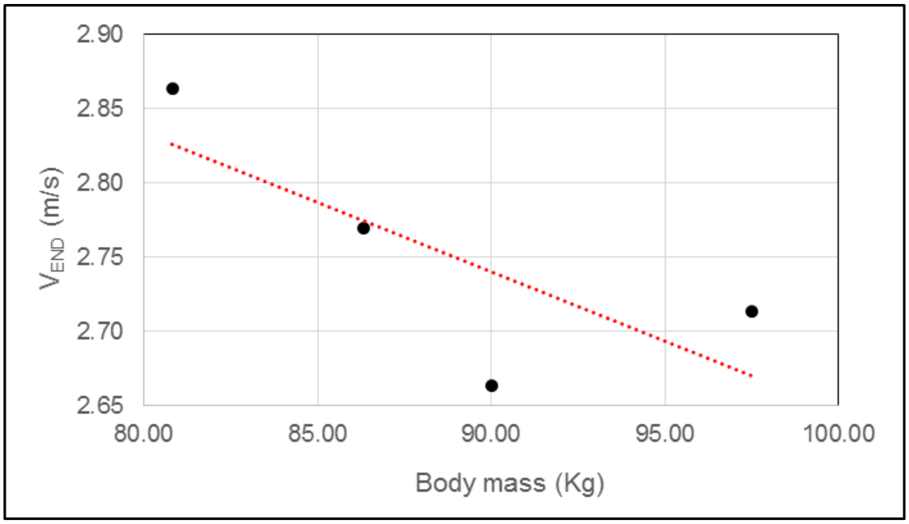


Figure 4-30. V_{END} versus body mass for the female subjects.

4.4 Discussion

The pull phase of the start is a key component for an overall successful start phase. As the timing system of a luge race is initiated at 5 m to 10 m from the start handles, it is crucial to reach this point of the track with the highest velocity possible.

The variables of V_{END} and V_{MAX} were considered as the outcome variables to help understand the pull phase mechanics. Nevertheless, V_{END} (velocity at the release of the handles) should be ultimately considered as the performance variable. It is inefficient from a performance point of view to achieve a high maximal velocity halfway through the pull phase if the athlete will not be able to maintain that velocity at the end of the sequence.

On average, all subjects reached their peak maximal velocity at 54% of the pull phase (from the $V_{COMP\text{-}ZERO}$ to V_{END}), which occurred at 0.302 sec of the 0.562 sec complete pull phase. Both male and female subjects showed a decrease in sled horizontal velocity from V_{MAX} to V_{END}. On Average, all athletes decreased velocity in 0.36± 0.17 m/s, females in 0.38±0.19 m/s and males on 0.33 ± 0.13 m/s. Similar results were found by Platzer et al. (2009) and Fedotova & Pilipiv (2012), where the maximum speed was higher than the end speed. Figure 4-11 illustrates the moderate influence ($r_s = 0.54$) of V_{MAX} on V_{END} when all subjects are analyzed. However, in the case of the females, V_{MAX} showed a negative correlation with V_{END} ($r_s = -0.560$) although not statically significant (Figure 4-12).

$RF/BW_{ZERO\text{-}END}$ seems to be the most important predictor for V_{END} ($r_s = 0.824$, p-value = 0.00). This was found when all the subjects were considered in the analysis together. Clear gender differences can be seen in Figures 4-16 and 4-17 in terms of the kinetic variables due to evident discrepancies in force production between male and female subjects. Differences in muscular strength between genders has been shown (Falkel, Sawka, Levtne, & Pandolf, 1985).

Females are particularly weaker in the upper body than the lower body compared to the males (Miller, MacDougall, Tarnopolsky, & Sale, 1993). The analysis of both groups shows the influence of most of the kinetic variables on the velocity at the release of the handles. Thus, although in the females no significant results were found for the kinetic variables from $V_{COMP-ZERO}$ to V_{END}, the influence of higher magnitudes of force produced and higher resultant V_{END} cannot be neglected. In the male group, most of the kinetic variables had a very high relationship with V_{END}.

Female subjects present a different strategy in the development of velocity compared to the males. For this group, V_{MAX} was highly influenced by $COMP_L$ and it seems to also be related to body mass (Figure 4-29). Heavier female subjects were able to achieve a higher maximum velocity but were not able to maintain this velocity through release of the handles. On the contrary, lighter female subjects showed a smaller deceleration from V_{MAX} to V_{END} (Figure 4-31 &Figure 4-32).

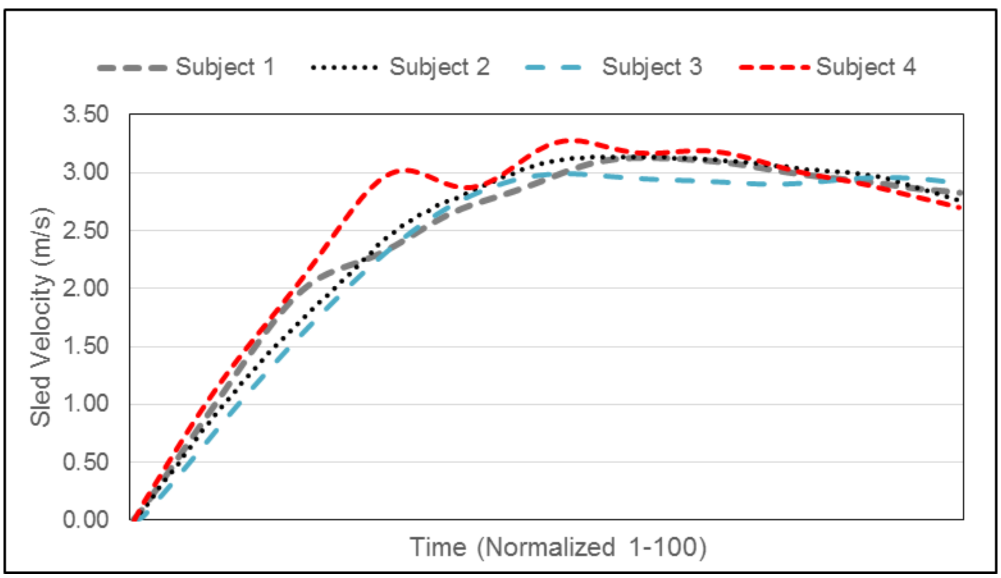


Figure 4-31. Average velocity curves for female subjects from $V_{COMP-ZERO}$ to V_{END}.

The ability to maintain sled velocity from V_{MAX} to V_{END} looks to be strongly related with the capacity to generate force throughout the last part of the movement relative to the subject's body mass ($RF/BW_{MAX\text{-}END}$, $r_s = 0.805$). As it can be observed in Figure 4-31, subject 4 achieves a maximal velocity of over 3.3 m/s, but it is unable to sustain this velocity and by the end of the pull phase V_{END} drops almost 0.6 m/s. Subject 3 on the contrary, is capable of maintaining that maximal velocity and even shows a positive acceleration in the final phase of the pull, corresponding to a higher magnitude in $RF/BW_{MAX\text{-}END}$ (Figure 4-32). This clearly indicates the necessity of high levels of strength in the upper extremity musculature relative to mass for female subjects.

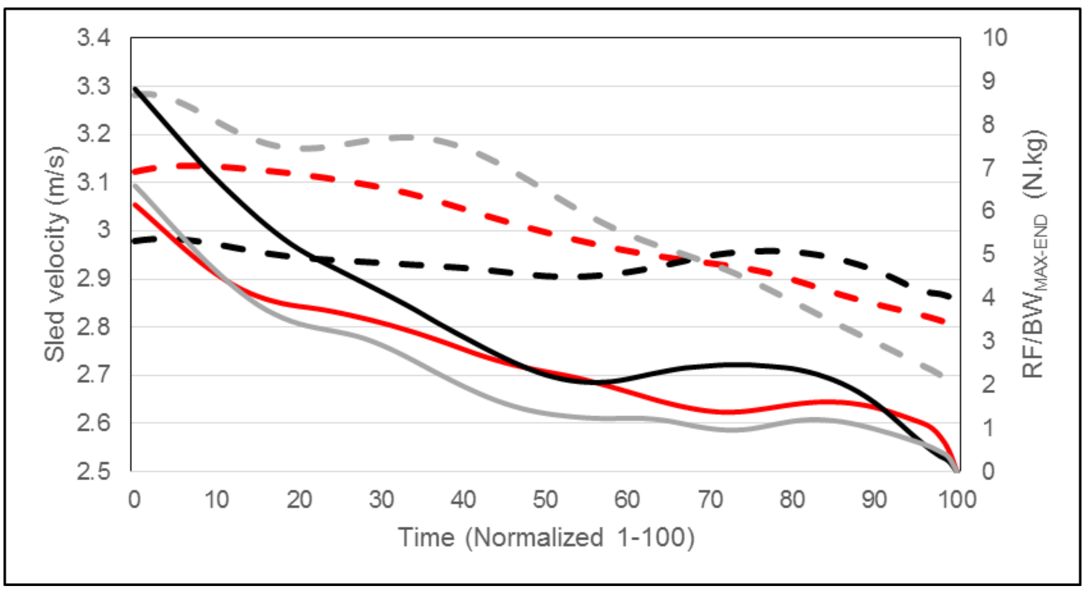


Figure 4-32. Average sled velocity curves from V_{MAX} to V_{END} for subject 1 (dashed red curve), subject 3 (dashed black curve) and subject 4 (dashed grey curve). Solid curves represent $RF/BW_{MAX\text{-}END}$ for each subject respectively.

On the other hand, male subjects were able to maintain the velocity accomplished during the first phase of the pull sequence. Although not statically significant, V_{MAX} presented a positive correlation with V_{END} ($\rho = 0.714$, p-value = 0.136) for the male subjects (illustrated in Figure 4-12). Contrary to the females, the heavier male subject was able to maintain the relative force production during the whole pull phase (Figure 4-33). For that reason, N-$Imp_{ZERO\text{-}END}$, N-$MF_{ZERO\text{-}END}$ and $RF/BW_{ZERO\text{-}END}$ were highly related to V_{END}.

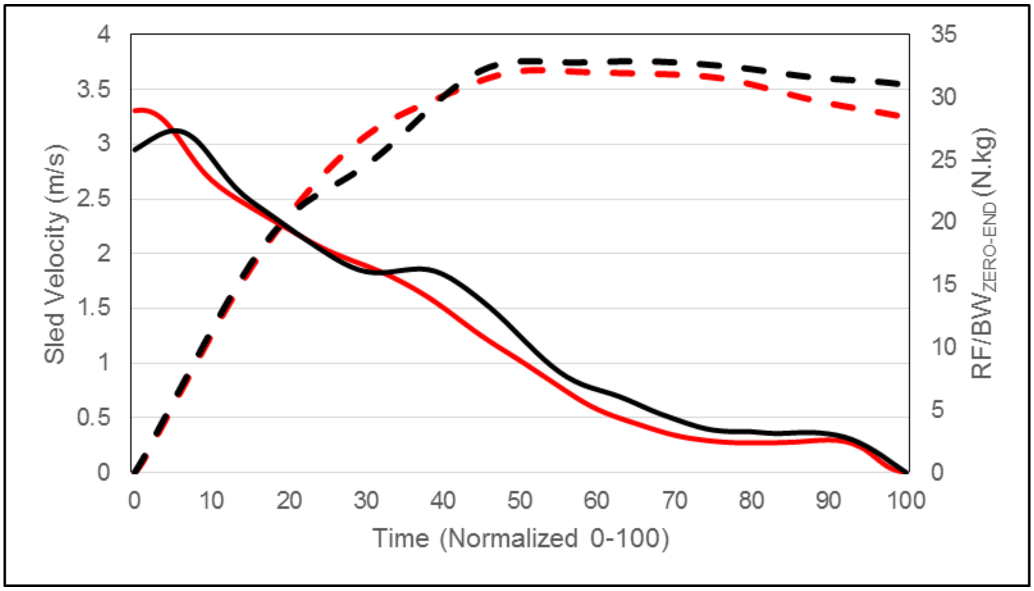


Figure 4-33. Average sled velocity curves (dashed curves) and $RF/BW_{ZERO\text{-}END}$ (solid curves) for subject 5 (red curve) and subject 6 (black curve) from $V_{COMP\text{-}ZERO}$ to V_{END}.

The relationship of body mass and V_{MAX} was also reported by Platzer et al (2009) with an R^2 of 0.532 (p-value = 0.019). However, in the same study body mass did not seem to have a relationship with V_{END} ($R^2 = 0.034$, p-value = 0.547). The highest predictor for V_{MAX} in the study by Platzer et al. (2009) was absolute isometric bench pull strength ($R^2 = 0.735$, p-value =0.001), but when V_{END} was the response variable of the regression model, relative isometric bench pull strength with body mass raised to the power of 0.67 was the highest predictor (R^2 = 0.731, p-value = 0.001). These results seem to be in agreement with the results described in this present study.

Crossland & Hartman (2011) also reported significant results for upper body strength measurements in particular for weighted 1 RM pull up and prone row. These results were analyzed in absolute values and not in relation to the subject body mass. The results from this study are also in agreement with the results of this thesis. However, it is uncertain to which phase of the start (Pull or Paddling phase) the results of Crossland & Hartman (2011) apply to as the performance criteria was overall start performance time.

The initial concentric muscular action of the pulling phase involves the contraction of the back extensor and shoulder extension musculature (Pull Phase 1). During this phase, subjects achieve maximal sled velocity and are close to reaching maximal back extension. Figures 4-34 and 4-35 exemplify the mechanics of the trunk extension and sled maximal velocity during the initial pull.

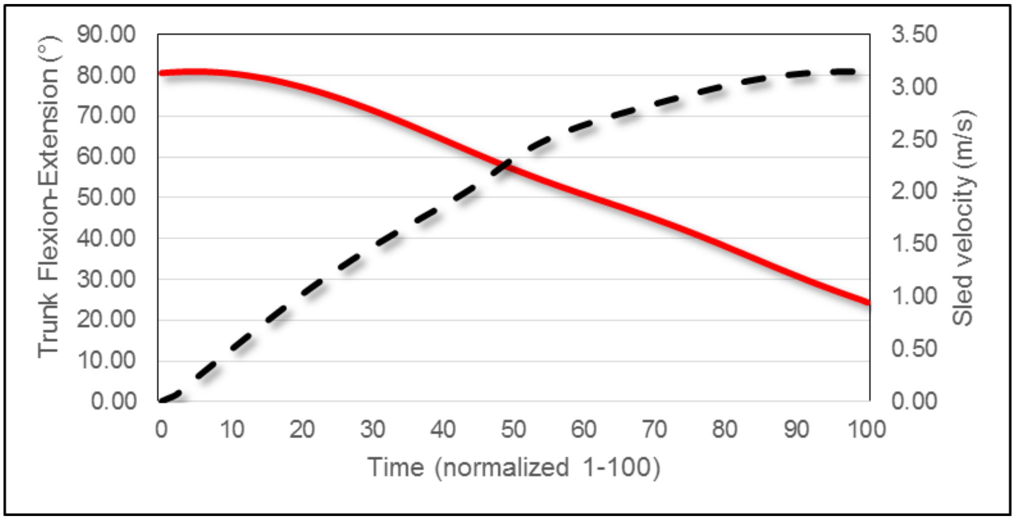


Figure 4-34. Trunk extension (solid red line) along with sled velocity (dashed black line) from $V_{COMP\text{-}ZERO}$ to V_{MAX}. For trunk extension, increasing positive values indicated flexion and decreasing values indicate extension. The maximal trunk flexion occurs at the compression phase when the sled reached the zero velocity point.

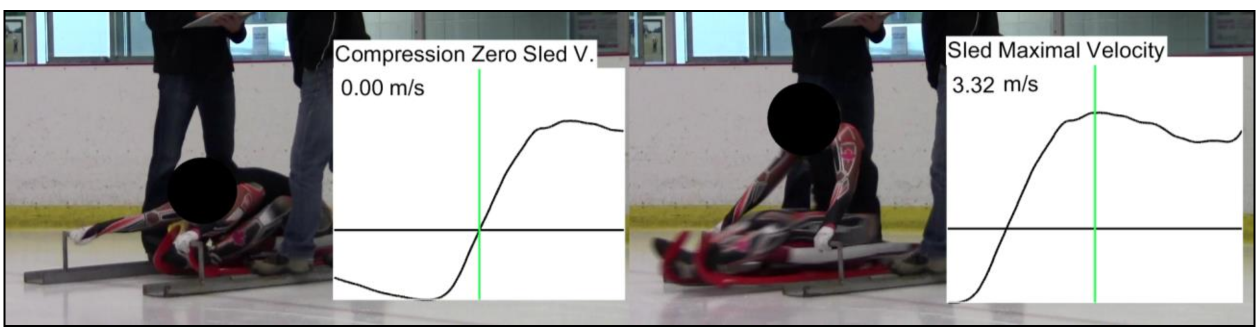


Figure 4-35. Example of trunk kinematics and the development of sled velocity during the Pull1 phase. During the Compression (left) subject achieves maximal trunk flexion, trunk extension and shoulder extension are responsible for the initial velocity development.

$\Delta TRUNK_{PEAK\text{-}MIN}$ showed a moderate relationship with V_{END} for all subjects. It is likely that this result is because male athletes showed higher end velocities than female athletes, resulting in a negative correlation between the two variables. When the data were stratified into males and females, $\Delta TRUNK_{PEAK-MIN}$ was insignificant with V_{END} and V_{MAX} for both groups. The variation in magnitude of trunk extension seems to have little or no relation with pull performance.

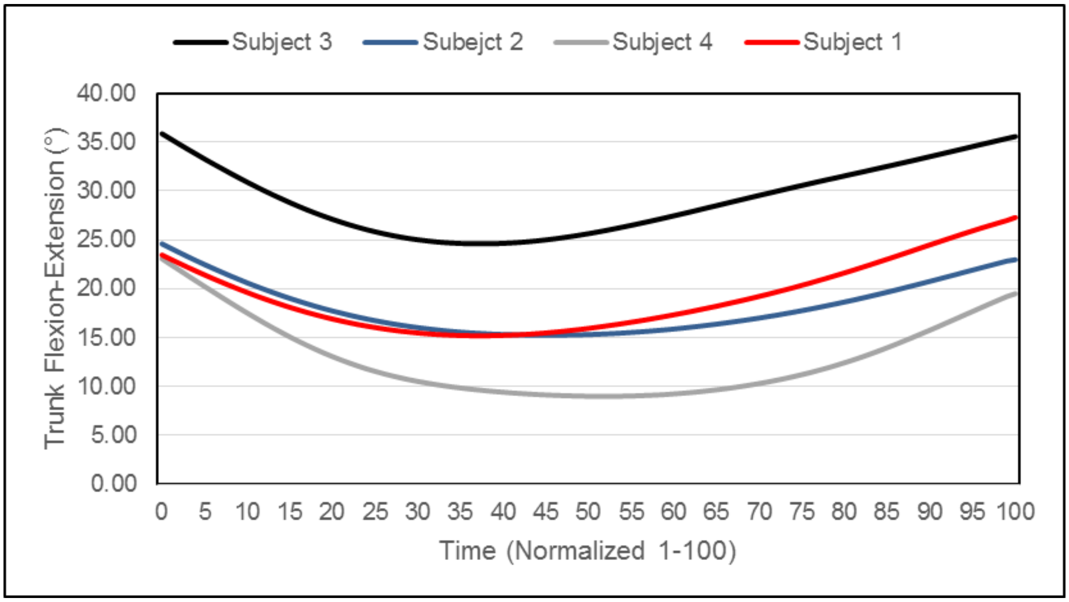


Figure 4-36. Trunk kinematics for V_{MAX} to V_{END} (female subjects). Subject 3 reached a maximal extension lower in magnitude and sooner (37%) than the rest of the female athletes (subject 1 – 40%; subject 2 – 46%; subject; subject 4-54%).

For the second phase of the pull (Figure 4-37), the upper extremity musculature becomes essential for force production and acceleration of the sled in terms of maintaining maximal velocity or preventing significant decelerations. Extension at the shoulder and elbow joint are the main force generators in the final phase of the pull. Left figure in Figure 4-37 shows the elbow flexion when the hips are passing the handles and the final thrust produced by elbow extension at the release (right figure in Figure 4-37)**.** This final part of the pull is crucial to maintain the velocity generated in the initial phase of the pull.

Figure 4-37. Second phase of the pull, after reaching maximal velocity, subjects initiate the last part of the movement where the goal is to maintain V_{MAX} and release the handles with the highest velocity as possible.

Subjects 3 and 6 showed the lowest reduction in sled velocity from maximal velocity (V_{MAX}) to velocity at the release of the handles (V_{END}) compared to the rest of the subjects. On average, subjects 3 and 6 achieved their maximal sled velocity at 0.283 seconds and 0.256 seconds at a distance of 0.52 m and 0.61 m respectively from the compression (Table 4-10). This creates the advantage of increasing the path to accelerate the sled and increasing the time of force application during the second phase of the pull.

Table 4-9. Summary of average distance travelled by the sled to V_{MAX} (D to V_{MAX}), time to V_{MAX}, total forward distance to V_{END}, time to V_{END} and the decrease in sled velocity from V_{MAX} to V_{END}.

Subject	D to V_{MAX} (m)	T to V_{MAX} (s)	D to End (m)	T to End (s)	V_{MAX} - V_{END} (m/s)
1	0.75	0.352	1.434	0.581	0.36
2	0.68	0.329	1.435	0.581	0.42
3	0.52	0.283	1.335	0.557	0.16
4	0.73	0.332	1.647	0.633	0.62
5	0.66	0.265	1.513	0.505	0.43
6	0.61	0.256	1.550	0.509	0.22

Luge female and male athletes have some of the largest BMI among the 2010 Winter Olympic athletes (Stanula et al., 2013). Body mass is certainly a key component for athlete selection criteria and race performance. Nevertheless, this chapter has demonstrated the importance of strength in relative terms to the mass of the subject and the implications to strength and power physical conditioning.

Heavier female subjects failed to maintain the maximal velocity produced during the initial pull. The scientific literature has shown the differences in body mass distribution between males and females and that increases in body weight for women represent a proportional increase in lower body muscle mass (Janssen et al., 2014). If female subjects with an increased body mass have a higher proportion of muscle distribution in the lower body than in the upper body (that would not represent a functional muscle mass during the Pull 2), that could explain why heavier female subjects failed to maintain maximal velocity through the end of the pull.

The limitations of this present study are related to the sample size. Only six elite luge athletes were recruited during this study; four females and two males. Statistical power is an issue to consider in this study. Gender comparison can be questionable based on the number of male subjects. The very high correlation coefficient and statistical significance found with the males athletes could be attributed to the amount of data available for analysis and the lack of variation in performance between the subjects.

Moreover, the population under study included only Canadian luge elite athletes. It is likely that the results from this thesis are only applicable to this particular population of athletes. There could be differences between luge athletes from different nations based on the coaching received during the development of the luge athletes and other physiological factors related to the athletes' training regime. Nonetheless, the results from this thesis are in agreement with the limited scientific literature available on the luge pull start.

Future studies should include larger sample sizes to make proper gender comparisons and include a more heterogeneous population made up of luge athletes from different nations. Also, an experimental approach controlling for load length, absence of load and manipulating compression distance could study the influence of the stretch-shortening cycle on luge start performance. A comprehensive analysis of various anthropometric parameters, in-lab strength-power measurements and their relation with the key performance indicators found in this thesis would be of interest for future studies.

4.5 Conclusion

The goal of this chapter was to investigate which biomechanical factors were associated with pull performance. To the author's knowledge, this is the first scientific study to analyze the pull phase kinetics and kinematics in elite luge athletes. The results from this chapter also set normative data and directions for future studies investigating the luge pull phase.

Key performance indicators were found, in particular for the kinetic variables with regards to body mass. Even though the sample size was small, gender differences were evident not only in terms of force production but also in the technical aspect and development of sled velocity throughout the pull phase.

For female athletes, the maximal velocity achieved during the pull phase appears to have an inverse relationship with end velocity, the relative force applied at the end of the pull is the most important factor in terms of performance. In the case of the males, the association between maximal and end velocity was inverse, having the kinetic variables during the entire pull a major impact on the final velocity.

The results of this thesis could have implications for strength and conditioning, physical testing and pull specific biomechanical testing. Also, because of the gender differences found in this chapter, there are new considerations in talent identification and athlete selection for prospective luge athletes.

Chapter Five: **Kinematic factors related with performance during the paddling phase of the luge start**

5.1 Introduction

The start phase plays a crucial role in the sport of luge. Like in other winter sliding sports, athletes spend most of the off-season training mastering start technique. For technical start training, coaches should be creative in replicating starts to parallel race-like conditions. The main challenge during the off season (which occurs in the spring-summer season for most of the countries competing in winter sliding sports) relates to the lack of availability of the race course due to environmental reasons. Also, performing start training on a competition track is not practical as lugers have to slide all the way down the track, which is rather inefficient for merely start technical training. As a consequence, coaches choose from various training methods and simulators to overcome these limitations.

Flat ice surfaces such as ice rinks, artificial indoor start ramps, wheeled luge sleds and adapted ergometers are among the different options that luge teams can choose from to enhance their paddling skills. Each of these different training methods have advantages and disadvantages. For instance, training on ice rinks allows coaches to manipulate the number of paddles per start, are optimal for start training volume and present the same surface characteristic as the real luge track. However, flat ice lacks the inclination of the start ramps that are seen in competition which could be an important factor to start training. Indoor start ramps overcome this issue but do not allow modification of the number of paddles performed after the pull because of their fixed length.

Even though ice rinks are flat, they are usually the method of preference for technical paddle training. Manipulating the number of paddles after the pull is a key aspect as every single start ramp has a different length; thus the number of arm strokes before assuming a race position (the "lay down") can vary from 2 to 7 paddles depending of the start ramp's length and inclination.

Turk-Noack (as cited in Lembert, Schachner, & Raschner, 2011) indicated that the paddles contribute 23% of the luge start performance. However, the absence of scientific publications and studies in this particular phase of the luge start have made it difficult to determine the biomechanical, physiological and anthropometric factors that influence paddling performance. Ideally, it is believed that luge athletes should increase their velocity at each contact of their hands with the ice and accelerate their sled as much as possible before assuming a lay down or race position. Lembert et al (2011) made some recommendations on efficient paddling technique. The authors mention that the fingers, wrist and elbow joints should be kept firm throughout each paddle for efficient force transfer. Also it was suggested that the back be straight and torso muscles tight as the athlete reaches forward to make contact with the ice. It is important to note that these were just suggestions made by the authors and have not been validated scientifically.

The aim of this present study is to determine the kinematic factors related to start performance during the paddling phase of the luge start in flat ice conditions. The following hypotheses were tested:

1. Paddle duration (time to complete three paddle cycles) is positively correlated with the change of horizontal sled velocity between the release from the handles to before the laydown.
2. Increases in horizontal sled velocity from the release of the handles to before the laydown is negatively correlated to paddle contact time.

3. An increased change in the magnitude of wrist extension from touchdown to take off at each paddle is negatively correlated with the change in horizontal sled velocity from the handles release to before the laydown.
4. There is a positive correlation between the change in horizontal sled velocity from the release of the handles to before laydown and trunk flexion magnitude at touchdown with the ice during the paddles.
5. A negative correlation exists between the change of horizontal sled velocity from the release of the handles to prior to the laydown with the magnitude of elbow flexion at each of the paddles.

These hypotheses were based on the current coaching knowledge and input from high performance luge coaches. Lambert et al. (2011) also made suggestions for the kinematics of the elbow and wrist joint which will be tested among the hypothesis in this Chapter.

5.2 Methods

5.2.1 Participants

A total of seven luge athletes ranging from 18 to 27 years old participated in the data collection sessions and all the subjects were part of the Canadian National Luge Team. Four of the participants were male with a $M_{age} = 21$ and the other three were female with a $M_{age} = 23.5$.

The sampling was similar as it was explained on Chapter 3 and Chapter 4 of this thesis. Subjects were recruited through the Canadian National Luge Team coach. The number of subjects was also dependant on the athletes' availability and competition calendar.

5.2.1.1 Inclusions

Athletes who trained at Canada Olympic Park (Calgary, Alberta), were members of the national luge team and were injury free at the moment were included in the study.

5.2.1.2 Exclusions

Subjects who did not compete during the last calendar season (2013-2014) were not included in the study.

5.2.2 Procedure

5.2.2.1 Ethics approval

The study was approved by The Conjoint Health Research Ethics Board of the University of Calgary (Study name: Kinematic and kinetic factors related with bobsleigh and luge start performance times of elite bobsleigh and luge athletes, Study ID: REB13-0574). All participants completed a written consent from (Appendix A).

5.2.2.2 Data Collection

Data collection sessions took place during the month of November 2014 at the ice hockey arenas located at Canada Olympic Park in Calgary, Alberta. The layout of the motion analysis cameras, portable luge handles and timing lights was similar to the layout described on the validation of the tri-axial wireless accelerometer (Chapter 3). The only substantial difference was the position of the motion capture cameras; two cameras were placed next to the luge handles and the rest of the cameras were located bilaterally at approximately 5 meters, 8 meters and 11 meters from the start handles and at approximately a 45 degree angle towards the capture volume (Figure 5-1). The centre of the capture volume was located at 5 meters from the luge start handles. The dimensions of the capture volume were the following: 5 meters in the anterior-posterior direction (+6 m, -6 m; X-axis), 2 meters in the medial-lateral direction (+1 m, -1 m; Y-axis) and 1.8 m in the vertical direction (+1.8, 0 m; Z Axis). Prior to each data collection session, the motion capture system was calibrated accordingly to the manufacturer's recommendations.

Additional timing lights were set up at 1.5 meters, 3.5 meters and 10.5 meters from the handles. In general, these timing light positions were chosen knowing that luge athletes perform the first paddle before the 3.5 metre mark and the second, third and fourth paddles prior to the 10 metre mark with respect to the start handles.

Figure 5-1. Motion Capture cameras layout on the ice rink

Subjects were asked to do their regular training warm up before placing the 19 mm diameter reflective markers on their body. Bilateral marker placement consisted of the following segments (three markers per segment with exception of the third metacarpal): one marker on the middle phalange of the third metacarpal, hand, forearm, arm, upper back and lower back (Figure 5-2). Markers were placed over the subject's luge suit with double sided Velcro and secured with duct tape. Additional bilateral markers were secured on the following anatomical landmarks for joint centre definition: styloid process of the ulna and radius, media and lateral epicondyles of the humerus, acromion process of the scapulae, anterior aspect of the head of the humerus, jugular notch and spinous process of T1 vertebrae. For sled velocity calculations, four markers were attached to the body of the sled.

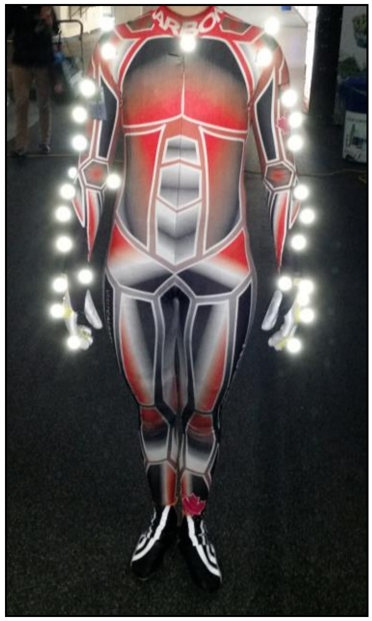


Figure 5-2. Subject with reflective markers ready for data collection

Static trials were similar as the trials described in Chapter 4 of this thesis. The protocol for data collection consisted of the following. Subjects were asked to perform pull starts at maximal effort and were required to perform four paddles before laying down on the sled. Once the athletes were in position to start, they were asked first to do all the preparatory movements they require before performing the start (Figure 5-3). The subject would nod to inform the investigators that he/she was prepared. Next, subjects were asked to remain steady for three seconds while the accelerometer was triggered to ensure a quiet period. After this quiet period, the investigators communicated to the athlete to perform their start. In the meantime, accelerometer, motion capture and timing data were collected. Systems were configured to collect data for 15 seconds with a sampling rate of 250 Hz for the motion capture system and 1024 Hz for the accelerometer.

Figure 5-3. Luge athlete in position to perform the start.

Subjects rested as much as they needed in between trials to ensure that each start would be performed with maximal effort and effects of fatigue were minimized. Equipment, mounting of the accelerometer and reflective markers were checked during the rest period to assure all was still secured properly. Subjects completed a total of three trials. If any errors occurred with the markers dislodging, motion capture system failing or accelerometer not collecting properly, the trial was repeated.

Antropometric data (mass and height) of each atlhete was provided by the luge team coaching staff corresponding to the date when the data collection sessions ocurred.

5.2.3 Data Analysis

Cortex Software (Motion Analysis Inc., Santa Rosa, CA, USA) was utilized to track and post process the motion capture data. The tracked motion capture data were exported to KinTrak software (Version 7, University of Calgary, Calgary, AB) for calculation of the desired kinematic variables. First, the static trials were imported into KinTrak for joint center definitions and application of transformation measurements to the trials corresponding to each subject.

Kinematic data corresponding to the subject's markers were filtered using a second order low-pass filter with a cut off frequency of 6 Hz and a second order low-pass filter with a cut off frequency of 15 Hz was applied to the markers which were placed on the sled. The sled velocity in the direction of travel was calculated by differentiating the markers attached to the back of the sled (Figure 5-4).

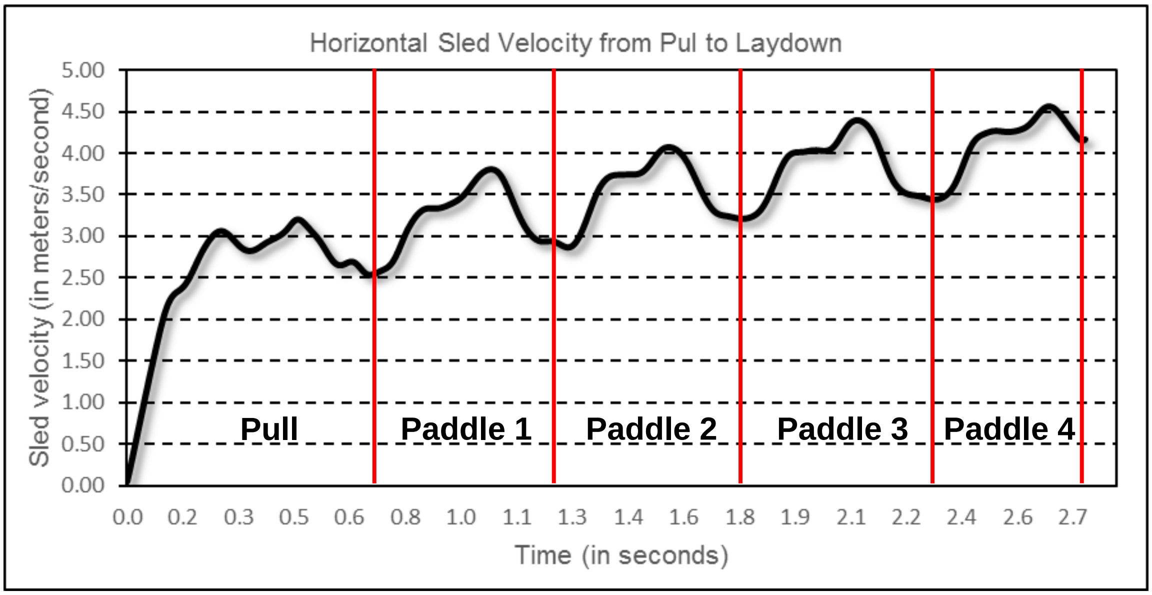


Figure 5-4. Horizontal sled velocity obtained by differentiation of the sled's markers. Five events can be identified from the continuous velocity profile: Pull, Paddle 1, Paddle 2, Paddle 3 and Paddle 4.

The performance criteria or dependent variable was defined as the change in horizontal sled velocity (ΔV_{SLED}, Figure 5-5) from paddle touchdown (P_{TD}) to paddle take off (P_{TO}) for each of the four paddles. Each of the four paddles (P1, P2, P3 and P4) was analyzed individually for the left and right hand.

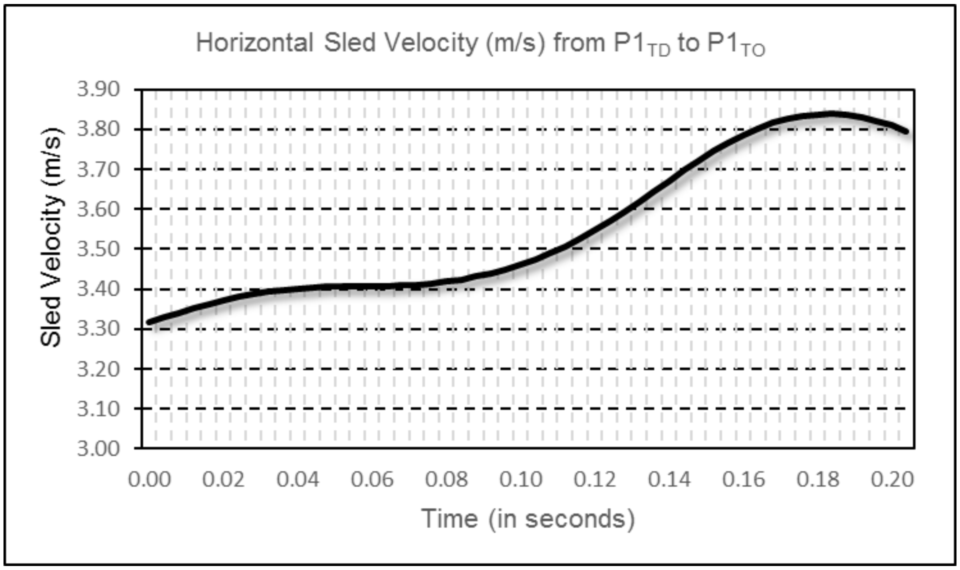


Figure 5-5. Horizontal sled velocity from the first paddle touchdown or contact with the ice to the paddle take off or loss of contact with the ice.

Paddle touchdown (P_{TD}) was defined from the vertical velocity of the marker located on the third metacarpal when the marker's vertical velocity was detected to be 0 m/s (Figure 5-6 & Figure 5-7). This was visually verified in the raw motion capture data. Paddle take off (P_{TO}) was identified from the same marker at the time where the marker's vertical velocity reached a negative velocity peak before crossing the zero velocity threshold (Figure 5-7). The same criteria were used for the left and right hand. As for the paddle contact time (P_{CT}), calculations were made from P_{TD} and P_{TO} for each of the four paddles bilaterally.

Also, the same marker on the right hand was used to calculate paddle length (P_L) from the marker's horizontal displacement. $P1_L$ was defined from the horizontal displacement of the marker between the paddle $P1_{TO}$ and the paddle $P2_{TD}$. The same procedure was used for the $P2_L$ ($P2_{TO}$ to $P3_{TD}$) and $P3_L$ ($P3_{TO}$ to $P4_{TD}$). However, it was not possible to calculate the length for paddle four as the subjects were instructed to lay down after the fourth paddle.

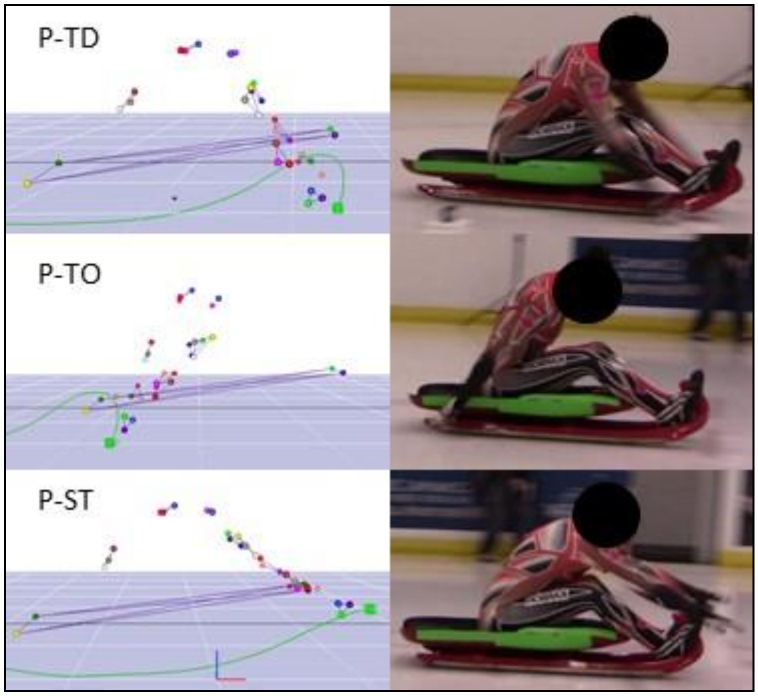


Figure 5-6. Paddle touchdown (P_{TD}), paddle take of (P_{TO}) and paddle swing phase represented on the motion capture data (left) and video footage (right).

The definition of P_{TD} and P_{TO} for each of the paddles allowed the estimation of the swing time (P_{ST}) and paddle cycle time (P_{CLT}) between paddles. For example, $P1_{ST}$ corresponded to the time between $P1_{TO}$ and $P2_{TD}$ and $P1_{CLT}$ the time between $P1_{TD}$-$P2_{TD}$. Paddle duration (P_{D-3}) was defined as the time required to perform three full paddle cycles, between the time markers defined as $P1_{TD}$ and $P4_{TD}$.

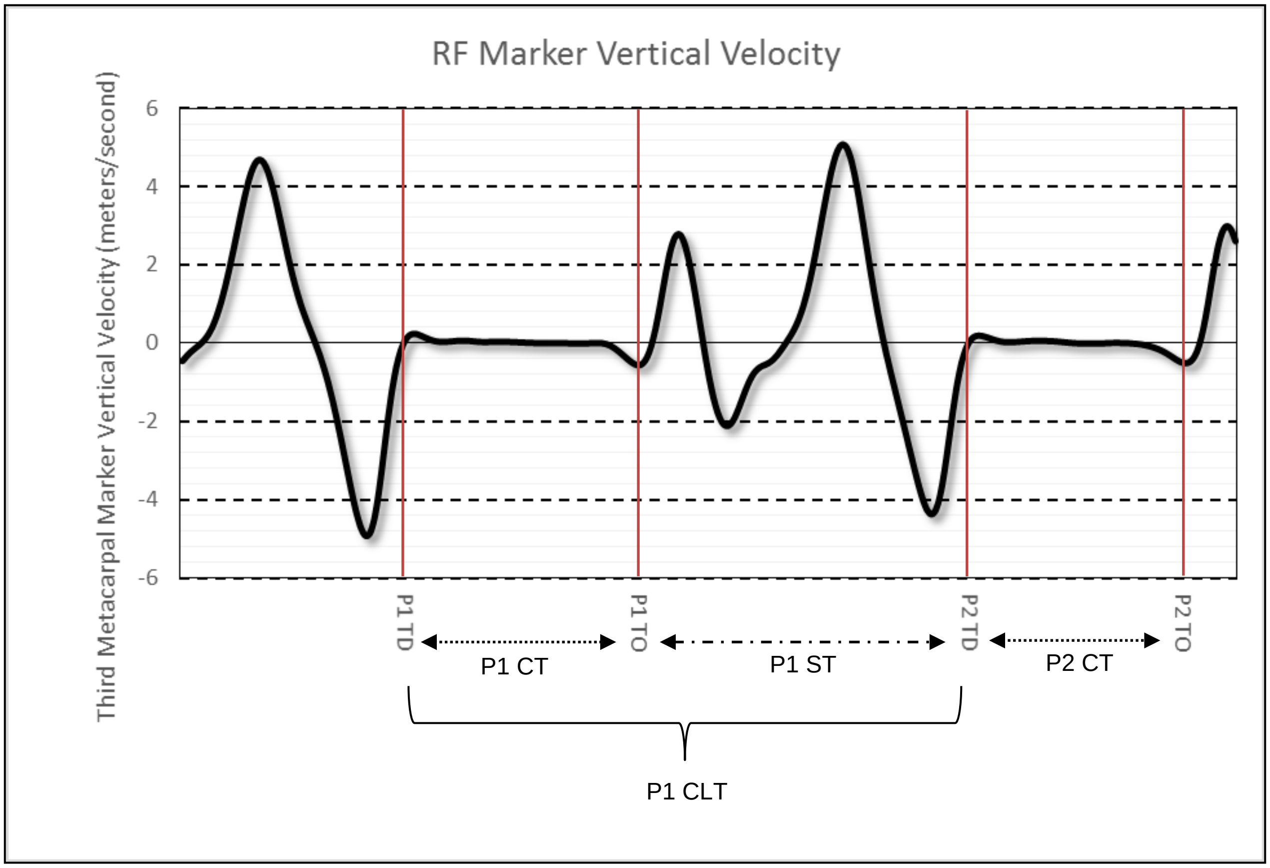


Figure 5-7. Vertical velocity of the right hand third metacarpal marker used to estimate paddle kinematics such as paddle contact time (P_{CT}), paddle swing time (P_{ST}) and paddle cycle time (P_{CLT}).

Bilateral upper extremity joint angles were calculated in KinTrak software as follows:

- Wrist joint: relative movement of the hand segment with respect of the forearm segment.
- Elbow joint: relative movement of the forearm segment with respect of the arm segment.
- Shoulder joint: relative movement of the arm segment with respect of the upper back.
- Upper back: relative movement of the upper back segment with respect of the lab coordinate system.

For subjects one and two, left wrist joint angles could not be calculated due to the absence of the left wrist joint center markers during the capture of the seated trials.

Maximal wrist extension for the left and right wrist ($RW_{PEAK-EXT}$ and $LW_{PEAK-EXT}$) were defined as the peak wrist extension between P_{TD} to P_{TO} for the four paddles (Figure 5-8). The change in magnitude of wrist extension ($RW_{\Delta EXT}$ & $LW_{\Delta EXT}$) was calculated from subtracting the wrist extension at P_{TD} ($RW_{EXT-PTD}$ and $LW_{EXT-PTD}$) from the $W_{PEAK-EXT.}$

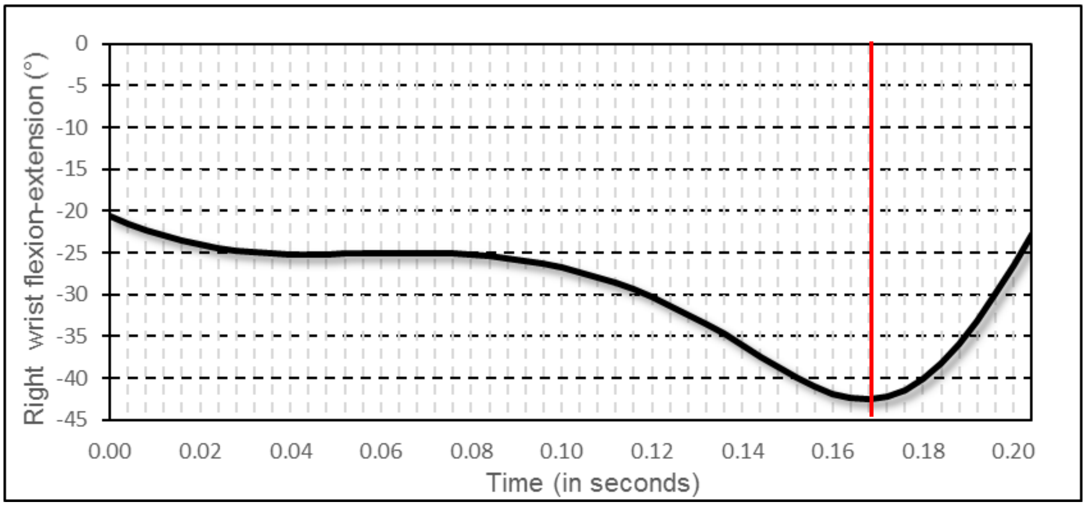


Figure 5-8. Right Wrist flexion-extension from $P2_{TD}$ to $P2_{TO}$, red straight line represents the $RW_{PEAK-EXT,}$ which was utilized to calculate the RWΔEXT. Increasing positive values indicate wrist flexion while negative values represent wrist extension.

Similarly, the peak elbow flexion between P_{TD} and P_{TO} was identified as the right and left maximal elbow flexion ($RE_{PEAK-FLEX}$ & $LE_{PEAK-FLEX}$). The right and left elbow flexion at touchdown ($RE_{EXT-PTD}$ and $LE_{EXT-PTD}$) was subtracted from the $RE_{PEAK-FLEX}$ & $LE_{PEAK-FLEX}$ to estimate the change in elbow flexion ($RE_{\Delta FLEX}$ & $LE_{\Delta FLEX}$) from P_{TD} to $RE_{PEAK-FLEX}$ & $LE_{PEAK-FLEX}$ (Figure 5-9).

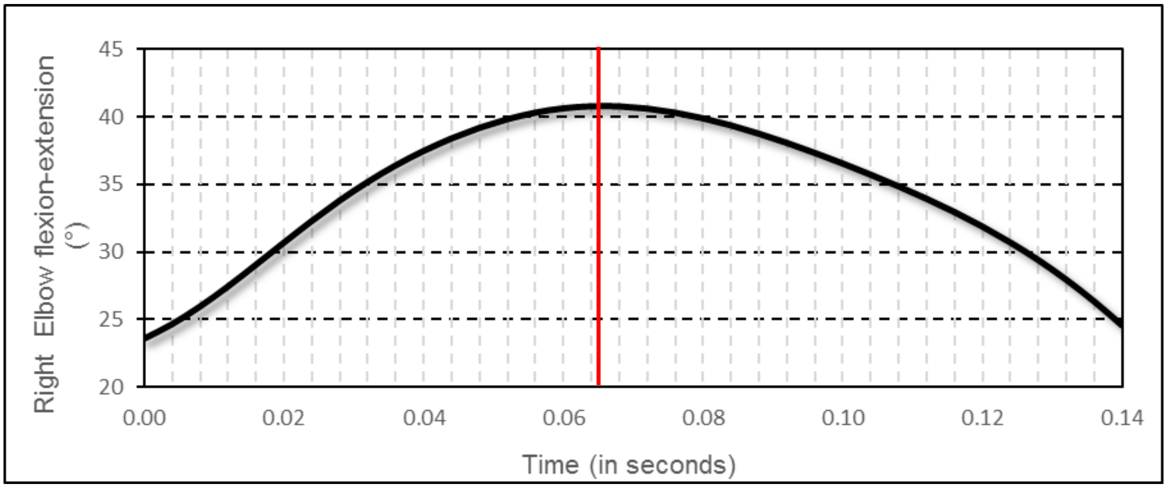


Figure 5-9. Right elbow flexion-extension from $P3_{TD}$ to $P3_{TO}$, P3-$RE_{PEAK\text{-}FLEX}$ being represented by the red straight line. Elbow flexion corresponds to increasing positive values whereas elbow extension is represented by decreasing values.

Trunk flexion at P_{TD} (TF_{TD}) was calculated from the three markers representing the upper back segment and in relation to the lab coordinate system (Figure 5-10).

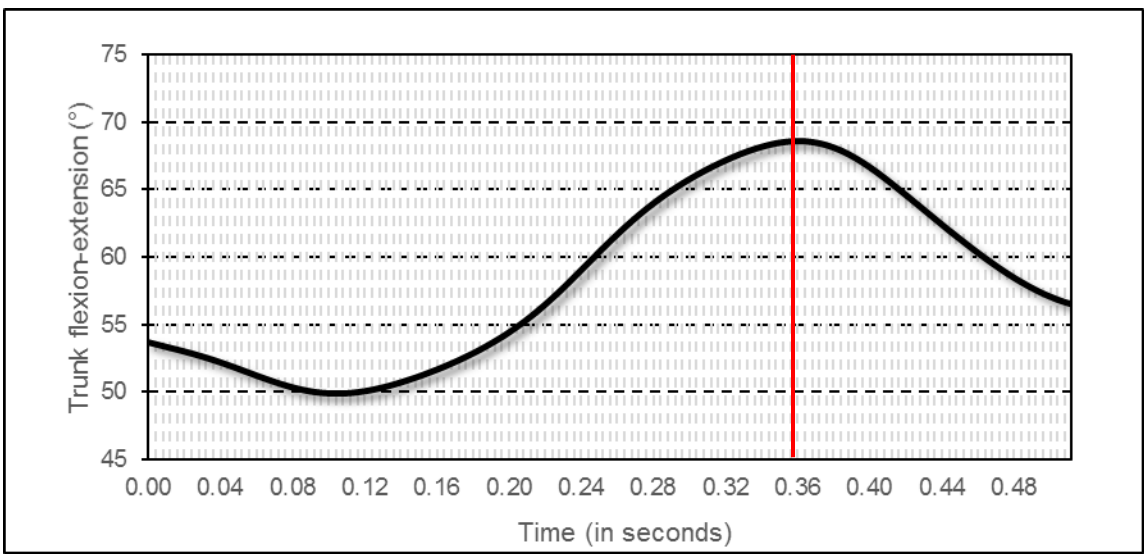


Figure 5-10. Trunk flexion-extension from $P2_{TO}$ to $P3_{TO}$. Increasing positive values indicate trunk flexion while decreasing values indicate trunk extension.

Data were statistically analyzed in Matlab software. Non parametric statistics were chosen for analysis due to the violation of the normality assumption and small sample size (n=7). Normality was assessed with normal probability distribution plots. Spearman rank correlation was used for correlation analysis between the independent and dependent variables. The correlation analysis was performed with the independent variable being the change in horizontal sled velocity at each paddle and the total change in horizontal sled velocity from $P1_{TD}$ to $P4_{TD}$. For the $P_{D\text{-}3}$, the change in velocity from $P1_{TD}$ to $P4_{TD}$ was considered as the dependent variable. Significance level was set to α=0.05 when assessing all the variables.

5.3 Results

The outcome variable was defined as the change in sled velocity from P_{TD} to P_{TO} at each paddle (Figure 5-11 and Figure 5-12) and also the ΔV_{SLED} from $P1_{TD}$ to $P4_{TD}$.

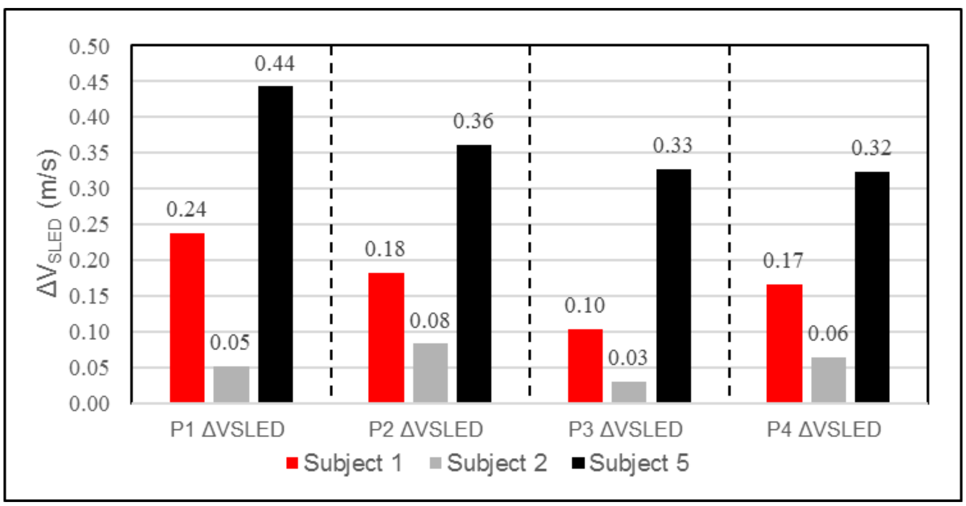


Figure 5-11. Average ΔV_{SLED} for Paddle 1 to Paddle 4 for female subjects. ΔV_{SLED} was defined as the variation in sled velocity from paddle touchdown (P_{TD}) to paddle take-off (P_{TO}).

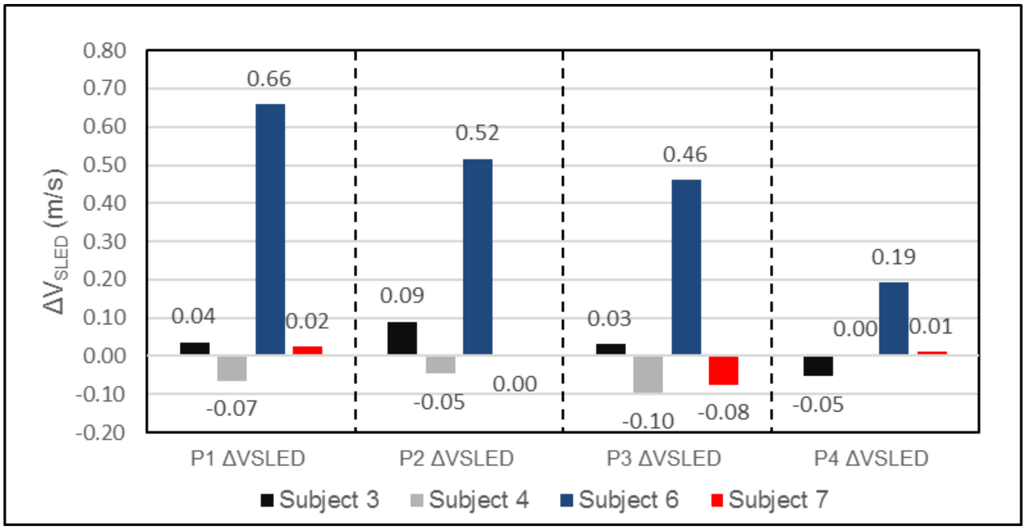


Figure 5-12. Average ΔV_{SLED} for Paddle 1 to Paddle 4 for male subjects. ΔV_{SLED} was defined as the variation in sled velocity from paddle touchdown (P_{TD}) to paddle take-off (P_{TO})

5.3.1 Paddle contact time and Paddle duration

The statistical analysis revealed that $R.P_{CT}$ and $L.P_{CT}$ was not correlated with paddling performance (Figure 5-13), nor with the ΔV_{SLED} at each paddle or the ΔV_{SLED} from $P1_{TD}$ to $P4_{TD}$ (Table 5-1).

Table 5-1. Summary of Spearman's Rank Correlation Coefficients (ρ) for the right hand paddle contact time ($R.P_{CT}$) and left hand paddle contact time ($L.P_{CT}$).

	P1 ΔV_{SLED}		**P2 ΔV_{SLED}**		**P3 ΔV_{SLED}**		**P4 ΔV_{SLED}**	
	R. P_{CT}	**L.P_{CT}**	**R. P_{CT}**	**L.P_{CT}**	**R. P_{CT}**	**L.P_{CT}**	**R. P_{CT}**	**L.P_{CT}**
ρ	0.084	-0.212	0.182	-0.181	0.314	-0.251	0.264	0.038
p-value	0.7168	0.368	0.429	0.413	0.165	0.272	0.247	0.869
	P1-P4 ΔV_{SLED}							
	RP1. P_{CT}	**LP1.P_{CT}**	**RP2. P_{CT}**	**LP2.P_{CT}**	**RP3. P_{CT}**	**LP3.P_{CT}**	**RP4. P_{CT}**	**LP4.P_{CT}**
ρ	0.240	-0.124	0.069	-0.33	-0.006	-0.338	-0.089	-0.1852
p-value	0.293	0.59	0.764	0.143	0.978	0.139	0.702	0.421

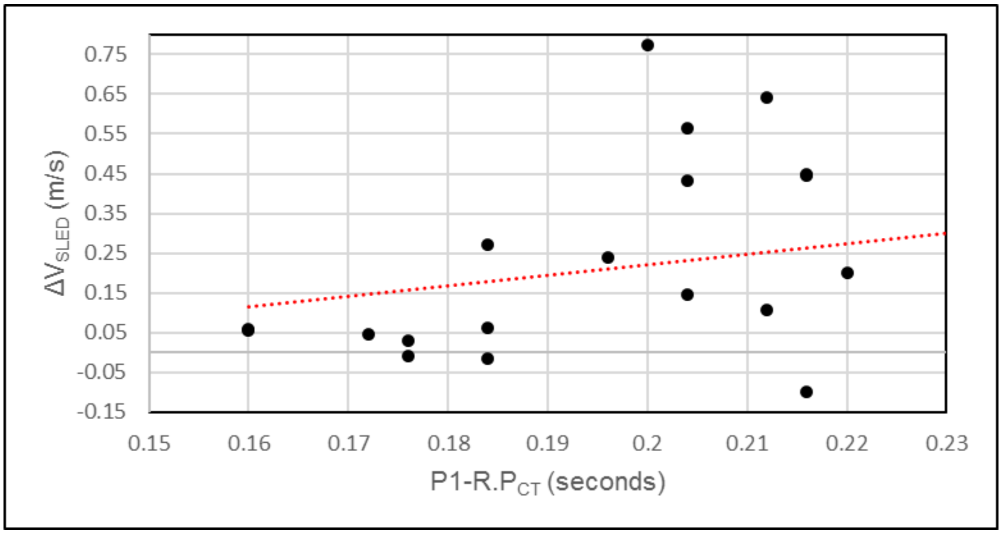


Figure 5-13. Scatter plot representing the relationship between P_{CT} and ΔV_{SLED} at P1 **(**$\rho = 0.084$, p-value=0.716).

Table 5-2 shows the correlation coefficients for males and females with relation to the ΔV_{SLED} at each paddle and R.P_{CT} and L.P_{CT}. None of the results were statically significant.

Table 5-2. Spearman correlation coefficients (**ρ**) for P_{CT} with ΔV_{SLED} from P1 to P4, data grouped by gender. Correlation coefficient at P3 (#) for male athletes could not be calculated due to missing data.

		Males				**Females**			
		P1	**P2**	**P3**	**P4**	**P1**	**P2**	**P3**	**P4**
R.P_{CT}	ρ	-0.127	-0.010	0.144	0.427	-0.034	0.187	-0.263	-0.585
	p-value	0.695	0.974	0.653	0.166	0.937	0.628	0.891	0.103
L.P_{CT}	ρ	-0.264	-0.101	#	-0.070	-0.326	-0.418	-0.289	-0.640
	p-value	0.431	0.753	#	0.827	0.389	0.261	0.444	0.087

Paddle duration (P_{D-3}) was not related with overall paddle performance (Figure 5-14), as it did not present a significant correlation (ρ= 0.159, p= 0.489) with P1-P4 ΔV_{SLED}. Similarly, there was no correlation between the two variables when the data were stratified into male (ρ= -0.363, p= 0.245) and female (ρ= 0.079, p= 0.777) groups.

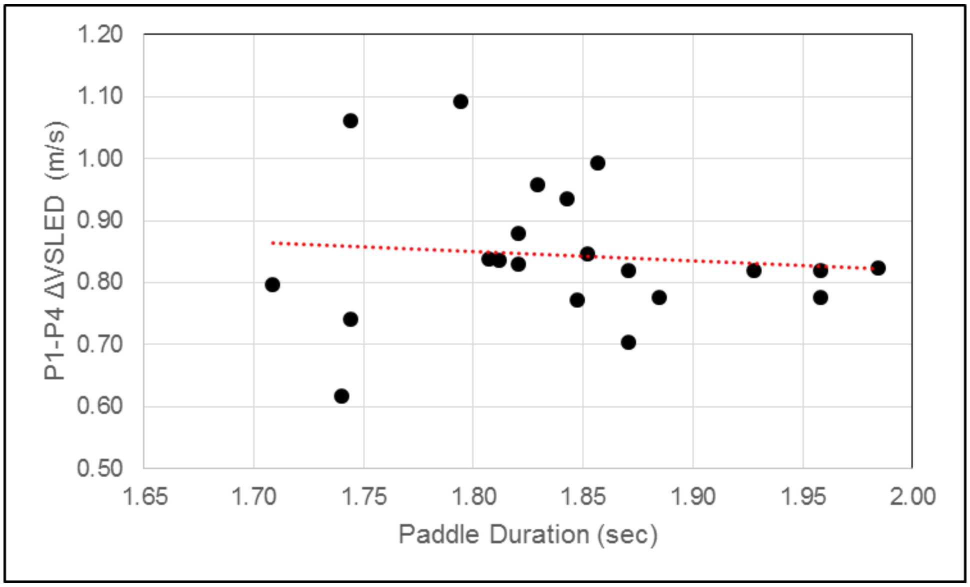


Figure 5-14. Scatter plot for P1-P4 ΔV_{SLED} and P_{D-3} for all subjects (ρ= 0.159, p= 0.489).

5.3.2 Change in magnitude of left and right wrist extension

The correlations between $RW_{\Delta EXT}$ and $LW_{\Delta EXT}$ with ΔV_{SLED} were weak and not significant overall except for $LW_{\Delta EXT}$ (ρ = 0.681, p-value=0.025) with ΔV_{SLED} at P4 (Table 5-3). Only 9 and 11 data points were available for LWΔEXT at P3 and P4 respectively (Figure 5-15).

Table 5-3. Spearman correlation coefficients (ρ) for $RW_{\Delta EXT}$ and $LW_{\Delta EXT}$ with ΔV_{SLED} (top table) from P1 to P4 and also with P1-P4 ΔV_{SLED} (bottom table). Results in bold and with an asterisk show statistical significance.

	P1		**P2**		**P3**		**P4**	
	$RW_{\Delta EXT}$	**$LW_{\Delta EXT}$**	**$RW_{\Delta EXT}$**	**$LW_{\Delta EXT}$**	**$RW_{\Delta EXT}$**	**$LW_{\Delta EXT}$**	**$RW_{\Delta EXT}$**	**$LW_{\Delta EXT}$**
ρ	-0.323	-0.075	0.05	-0.06	0.226	0.55	0.026	**0.681***
p-value	0.152	0.7926	0.827	0.832	0.323	0.132	0.908	**0.025***
	P1-P4 ΔV_{SLED}							
	$RW_{\Delta EXT}$	**$LW_{\Delta EXT}$**	**$RW_{\Delta EXT}$**	**$LW_{\Delta EXT}$**	**$RW_{\Delta EXT}$**	**$LW_{\Delta EXT}$**	**$RW_{\Delta EXT}$**	**$LW_{\Delta EXT}$**
ρ	-0.275	0.149	-0.120	0.155	-0.005	0.669	-0.012	0.182
p-value	0.227	0.59	0.602	0.581	0.979	0.054	0.959	0.591

Grouping by gender was not performed for the $RW_{\Delta EXT}$ and $LW_{\Delta EXT}$ due to the small number of data points present for correlation analysis.

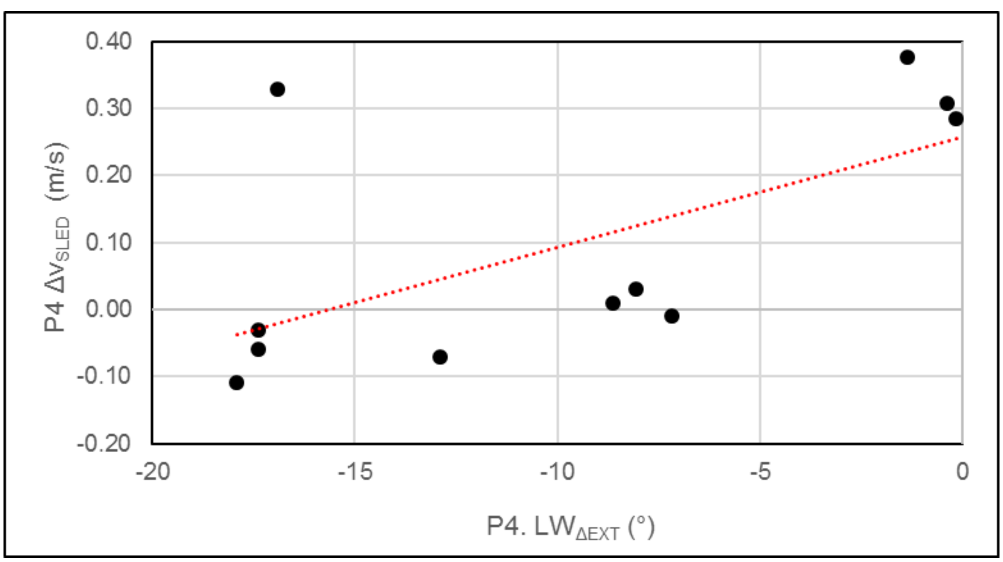


Figure 5-15. P4 ΔV_{SLED} and P4.$LW_{\Delta EXT}$ presented a linear positive correlation, although only 11 trials from 4 different subjects were used in this analysis (ρ = 0.681, p-value = 0.025)

5.3.3 Change in magnitude of elbow flexion

$RE\Delta_{FLEX}$ and $LE\Delta_{FLEX}$ do not seem to have a relation with overall paddling performance during the luge start. However, significant correlations were found for female athletes at the 2nd and 4th paddle. P2 $LE\Delta_{FLEX}$ showed a significant high correlation of $\rho = -0.75$ ($p = 0.025$). At P4, $RE\Delta_{FLEX}$ and $LE\Delta_{FLEX}$ were also high correlations and statistically significant (Figure 5-16). Correlation coefficients are summarized in Table 5-4 for all subjects (♂ & ♀), male (♂) and female (♀) subjects.

Table 5-4. Summary of Spearman correlation coefficients, # denotes coefficients that were not calculated because of missing data. Results in bold and with an asterisk showed statistical significance.

	P1		**P2**		**P3**		**P4**	
♂ & ♀	**REΔFLEX**	**LEΔFLEX**	**REΔFLEX**	**LEΔFLEX**	**REΔFLEX**	**LEΔFLEX**	**REΔFLEX**	**LEΔFLEX**
ρ	-0.345	-0.167	0.048	-0.353	0.115	0.209	0.229	0.226
p-value	0.125	0.466	0.836	0.116	0.616	0.361	0.317	0.398
♂	**REΔFLEX**	**LEΔFLEX**	**REΔFLEX**	**LEΔFLEX**	**REΔFLEX**	**LEΔFLEX**	**REΔFLEX**	**LEΔFLEX**
ρ	-0.604	-0.23	0.118	-0.35	-0.062	0.251	0.529	#
p-value	0.042	0.466	0.716	0.256	0.851	0.43	0.076	#
♀	**REΔFLEX**	**LEΔFLEX**	**REΔFLEX**	**LEΔFLEX**	**REΔFLEX**	**LEΔFLEX**	**REΔFLEX**	**LEΔFLEX**
ρ	-0.216	-0.283	-0.533	**-0.75***	-0.316	-0.466	**-0.75***	**-0.816***
p-value	0.58	0.463	0.147	**0.025***	0.41	0.212	**0.025***	**0.0108***

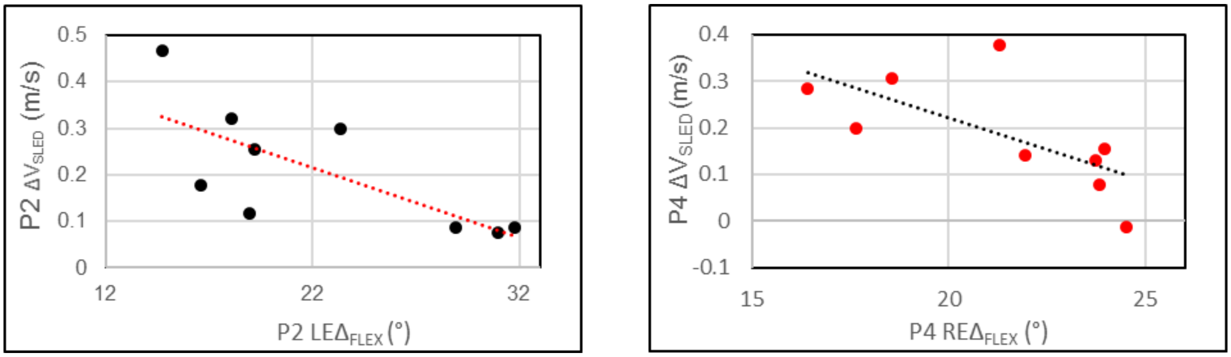


Figure 5-16. Scatter plots for P2 $LE\Delta_{FLEX}$ (ρ = -0.75, p-value = 0.025) and P4 $RE\Delta_{FLEX}$ (ρ = -0.75, p-value = 0.025) and ΔV_{SLED} at the respective paddles in female athletes.

5.3.4 Trunk flexion at paddle touchdown

TF_{TD} is not related with ΔV_{SLED} during the paddles. No significant results were found between these two variables even when the data were stratified into males and females. At best, TF_{TD} had a moderate correlation (ρ = 0.5) with a p-value = 0.097 for the male subjects (Table 5-5).

Table 5-5. Correlation coefficients for trunk flexion at paddle touchdown (TF_{TD}) with ΔV_{SLED} for P1 to P4. Data presented for both groups, male (♂) and female (♀). P4-TF_{TD} could not be calculated for the female athletes due to missing data.

	P1			**P2**			**P3**			**P4**		
	All	♂	♀	All	♂	♀	All	♂	♀	All	♂	♀
ρ	0.202	0.419	-0.483	0.267	0.468	-0.433	0.277	0.363	-0.266	0.283	0.5	#
p-value	0.376	0.176	0.193	0.24	0.127	0.249	0.221	0.246	0.493	0.213	0.097	#

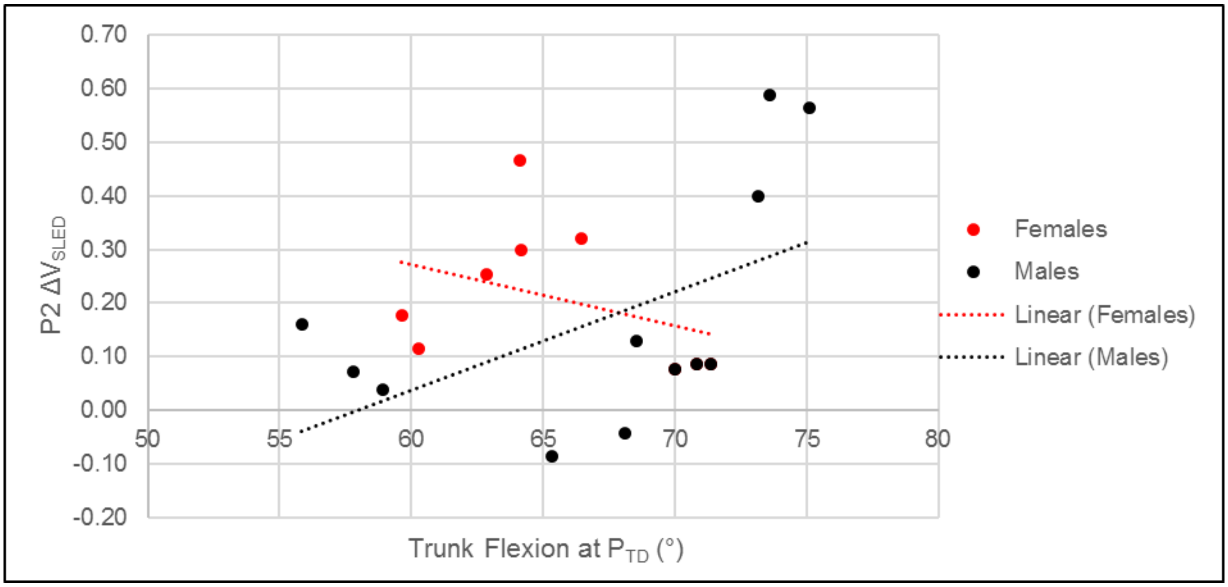


Figure 5-17. P2ΔV_{SLED} vs P2 TF_{TD} for male and female athletes, trend lines show the inverse relationship for this variable between genders.

5.3.5 Additional data analysis and results

The velocity curves from the different subjects were studied and analyzed to understand how luge athletes accelerate during the paddling phase of the start. In the previous analysis, the outcome variable was defined as the change in sled velocity from paddle touchdown to paddle take off for the four different paddles. As it can be seen in Figure 5-11 and Figure 5-12, some subjects do not accelerate through the paddles. The analysis incorporated the following variables to understand the different strategies luge athletes use to increase their velocity:

- Pull velocity (V_{PULL}): maximal horizontal sled velocity achieved during the pull phase.
- Change in velocity from V_{PULL} to paddle 1 touchdown ($\Delta V_{P\text{-}P1}$)

- Change in velocity from $P1_{TO}$ to $P2_{TD}$ ($\Delta V_{P1\text{-}P2}$)
- Change in velocity from $P2_{TO}$ to $P3_{TD}$ ($\Delta V_{P2\text{-}P3}$)
- Change in velocity from $P3_{TO}$ to $P4_{TD}$ ($\Delta V_{P3\text{-}P4}$)

Average values from the above mentioned variables are represented on Figure 5-18 for female subjects and Figure 5-19 for male subjects. Subject 2 for example, showed increases in velocity mostly achieved through the swing phase (average $\Delta V_{P1\text{-}P2}$ = 0.19 m/s) rather than by the propulsion achieved through the paddling motion (during hand contact) (average P2 ΔV_{SLED} = 0.08 m/s). On the contrary, subject 5 gained higher velocities trough the paddles (average P2 ΔV_{SLED} = 0.36 m/s) and decelerated during the swing phase (average $\Delta V_{P1\text{-}P2}$ = -0.06 m/s).

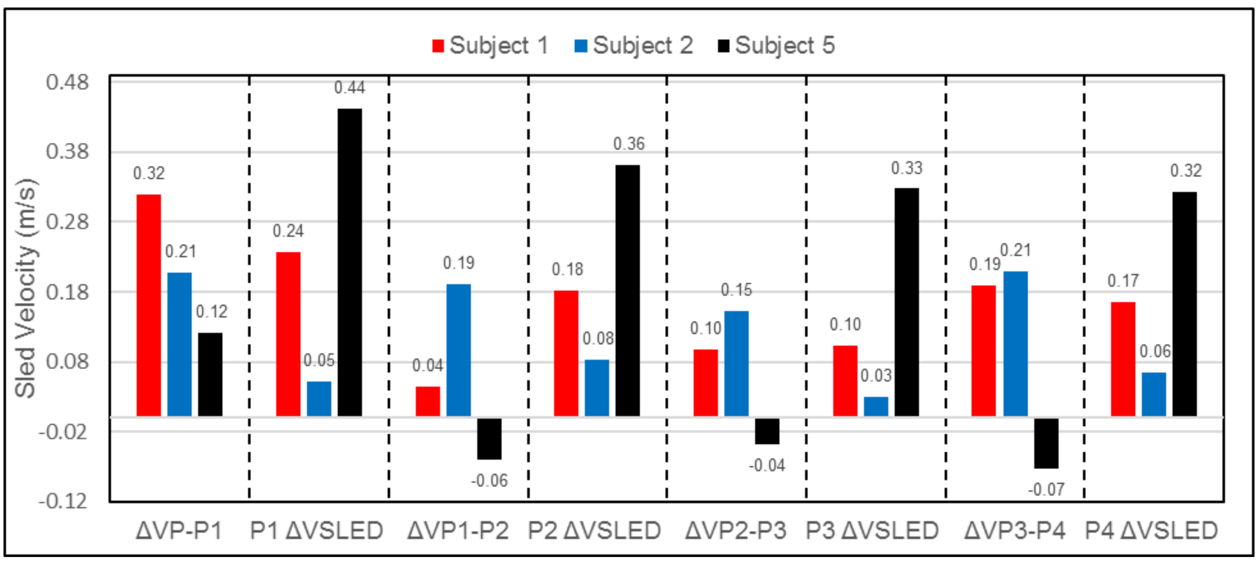


Figure 5-18. Mean velocities for $\Delta V_{P\text{-}P1}$, $\Delta V_{P1\text{-}P2}$, $\Delta V_{P2\text{-}P3}$ and $\Delta V_{P3\text{-}P4}$ with also mean velocities for ΔV_{SLED} for P1, P2, P3 and P4 (Female subjects).

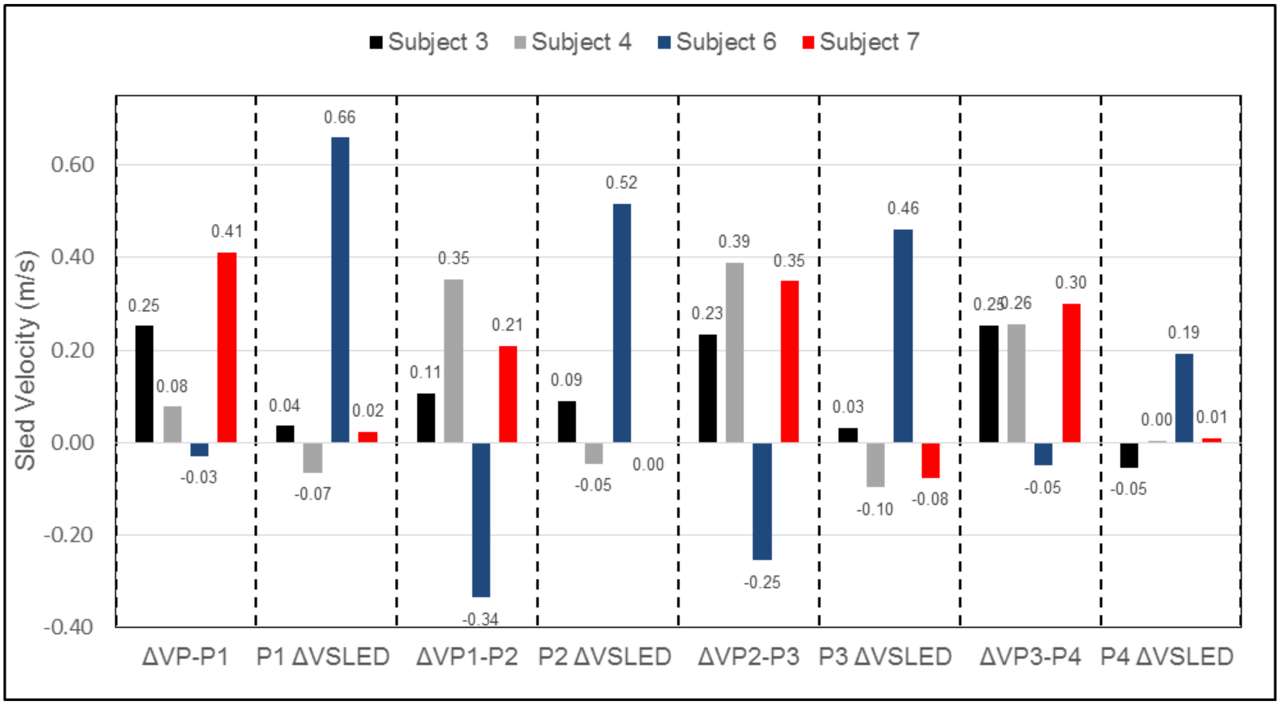


Figure 5-19. Mean velocities for $\Delta V_{P\text{-}P1}$, $\Delta V_{P1\text{-}P2}$, $\Delta V_{P2\text{-}P3}$ and $\Delta V_{P3\text{-}P4}$ with also mean velocities for ΔV_{SLED} for P1, P2, P3 and P4 (male subjects).

Similar to the data presented for the female athletes, two very different strategies can be observed in the data for the male subjects. Subject 6, clearly gains velocity trough the paddles (contact) while the rest of the male subjects do this during the swing phases.

The ability to increase velocity through the swing phase seems to be related with a higher body mass. Also, subjects with lower mass achieved higher velocities while in contact with the ice (Figure 5-20 & Figure 5-21).

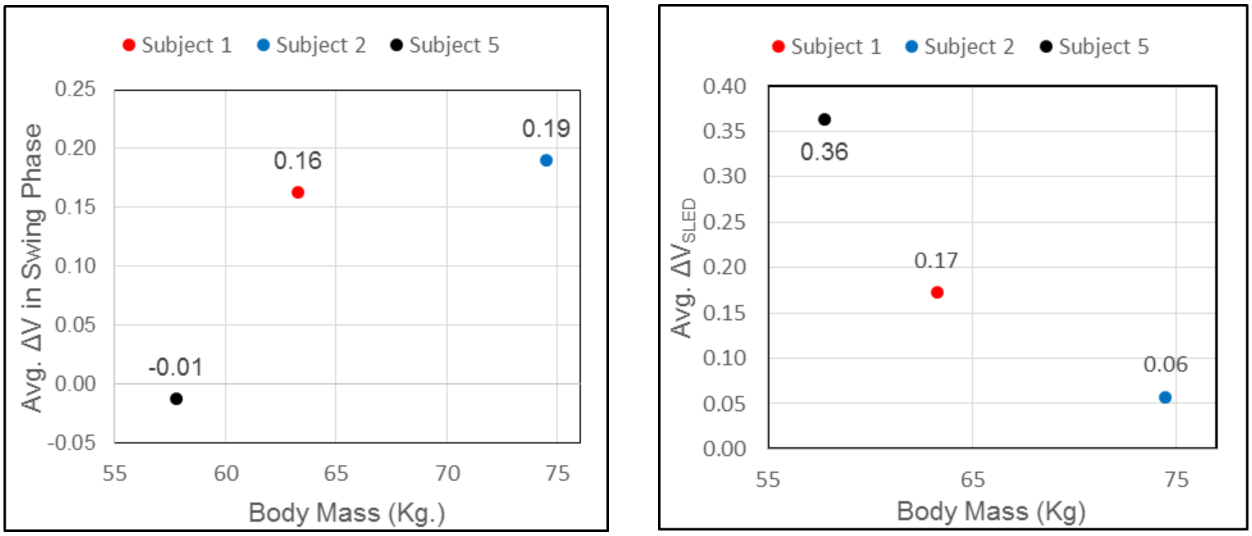


Figure 5-20. Scatter plots for average change in velocity during the swing phase ($\Delta V_{P\text{-}P1}$, $\Delta V_{P1\text{-}P2}$, $\Delta V P_{2\text{-}P3}$ and $\Delta V_{P3\text{-}P4}$) in relation to body mass (left graph) and average ΔV_{SLED} from P1 to P4 also with relation to body mass (right chart) for female subjects.

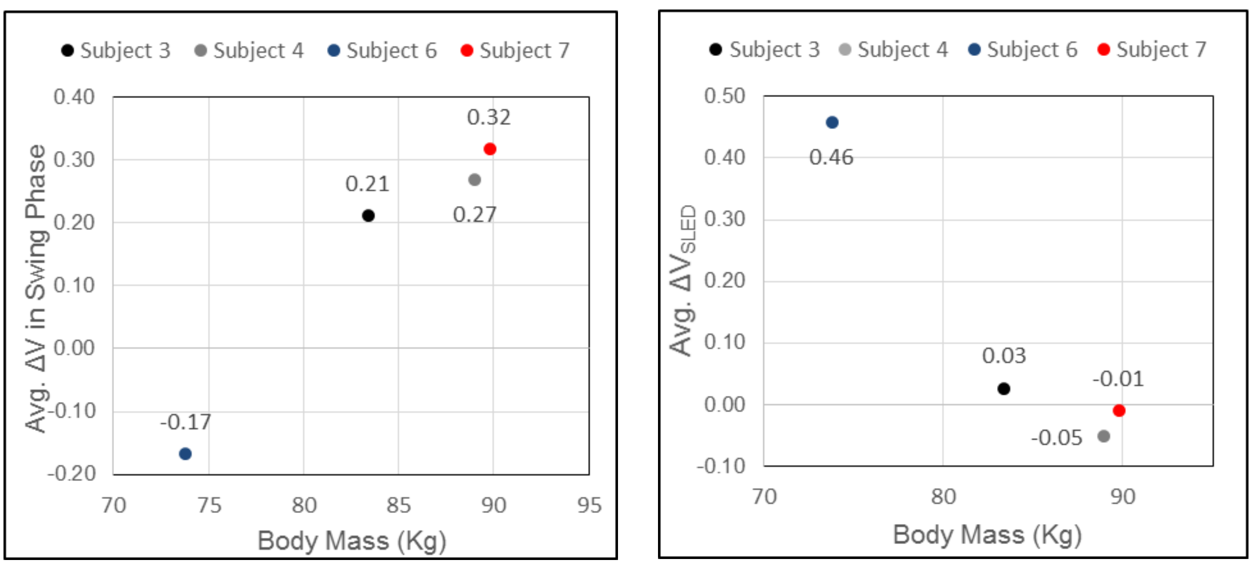


Figure 5-21. Scatter plots for average change in velocity during the swing phase ($\Delta V_{P\text{-}P1}$, $\Delta V_{P1\text{-}P2}$, $\Delta V P_{2\text{-}P3}$ and $\Delta V_{P3\text{-}P4}$) in relation to body mass (left chart) and average ΔV_{SLED} from P1 to P4 also with relation to body mass (right chart) for male subjects.

A Pearson Correlation Coefficient matrix analysis was also performed among several velocity variables including V_{PULL} and sled horizontal velocity at P_{TD} and P_{TO} from Paddle 1 to Paddle 4. Statistical results were significant (p-value <0.05) with high to very high correlation coefficients across the multiple velocity points (Table 5-6).

Table 5-6. Pearson Correlation Matrix for different velocity points from the continuous velocity profile during the paddling phase.

	V_{PULL}	$P1_{TD}$	$P1_{TO}$	$P2_{TD}$	$P2_{TO}$	$P3_{TD}$	$P3_{TO}$	$P4_{TD}$	$P4_{TO}$
V_{PULL}		0.939	0.863	0.951	0.888	0.940	0.891	0.949	0.873
$P1_{TD}$	0.939		0.808	0.982	0.823	0.976	0.830	0.966	0.859
$P1_{TO}$	0.863	0.808		0.852	0.982	0.835	0.963	0.906	0.934
$P2_{TD}$	0.951	0.982	0.852		0.868	0.991	0.877	0.983	0.901
$P2_{TO}$	0.888	0.823	0.982	0.868		0.857	0.988	0.916	0.962
$P3_{TD}$	0.940	0.976	0.835	0.991	0.857		0.867	0.983	0.899
$P3_{TO}$	0.891	0.830	0.963	0.877	0.988	0.867		0.917	0.977
$P4_{TD}$	0.949	0.966	0.906	0.983	0.916	0.983	0.917		0.934
$P4_{TO}$	0.873	0.859	0.934	0.901	0.962	0.899	0.977	0.934	

5.4 Discussion

The statistical analysis revealed that overall there is not enough scientific evidence to support the different hypothesis discussed in this chapter. The only variable that presented significantly high correlations with performance was $LE\Delta_{FLEX}$ at P2 and P4 and $RE\Delta_{FLEX}$ at P4 for the female subjects. Perhaps due to the sample size in the study the same relationship was not found across the four paddles.

Performance was defined as the change in magnitude of horizontal sled velocity from the moment of paddle touchdown to the take-off at each of the four paddles. The expected outcome from the contact phase during the paddles would be an increase in velocity due to the ground reaction forces accelerating the sled in the forward direction. However, subjects increased their velocity by means of two very different mechanisms (Figure 5-22). Four of the 7 subjects (3 males and 1 female) increased their velocity from the pull phase to the $P4_{TD}$ exclusively during the swing phase (swinging of their arms in the air). One female subject increased sled velocity both through the paddles and the swing phase. Two subjects achieved considerably greater velocities through the paddles and did not show gains (even decelerated) in velocity during the swing phase.

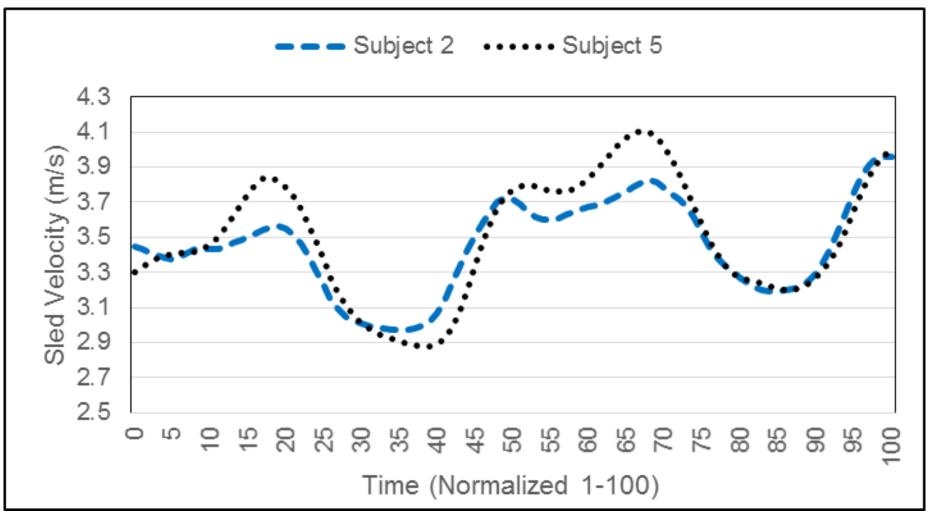


Figure 5-22. Velocity curves for two female athletes from $P1_{TD}$ to $P3_{TD}$. Subject 2 gains little velocity through the paddles and achieved a higher momentum with the swing of the arms. Subject 5 showed the opposite scenario and showed decreases in velocity during the swing phase but gained significantly during the paddles.

From a coaching perspective it is believed that during the contact phase of the paddles, a luge athlete needs to maintain the wrist and elbow joints in a stiff or in a “locked” position. Excessive wrist extension and elbow flexion during the paddle contact phase would be detrimental for performance. As it was previously mentioned, there was not enough evidence in this chapter to confirm this hypothesis during the four paddles. Nevertheless, female subject five who achieved the highest average sled velocity for the females (3.64 m/s) from $P1_{TD}$ to $P4_{TD}$ and accelerated the sled by contact with the ice (Figure 5-23) presented significantly different wrist joint kinematics (Figure 5-24) compared to subject one (average sled velocity = 3.54 m/s) and subject two (average sled velocity = 3.39 m/s). Subject five maintained a “firm” wrist joint through the paddle contact phase while subjects one and two had a considerable amount of wrist breaking (Figure 5-24).

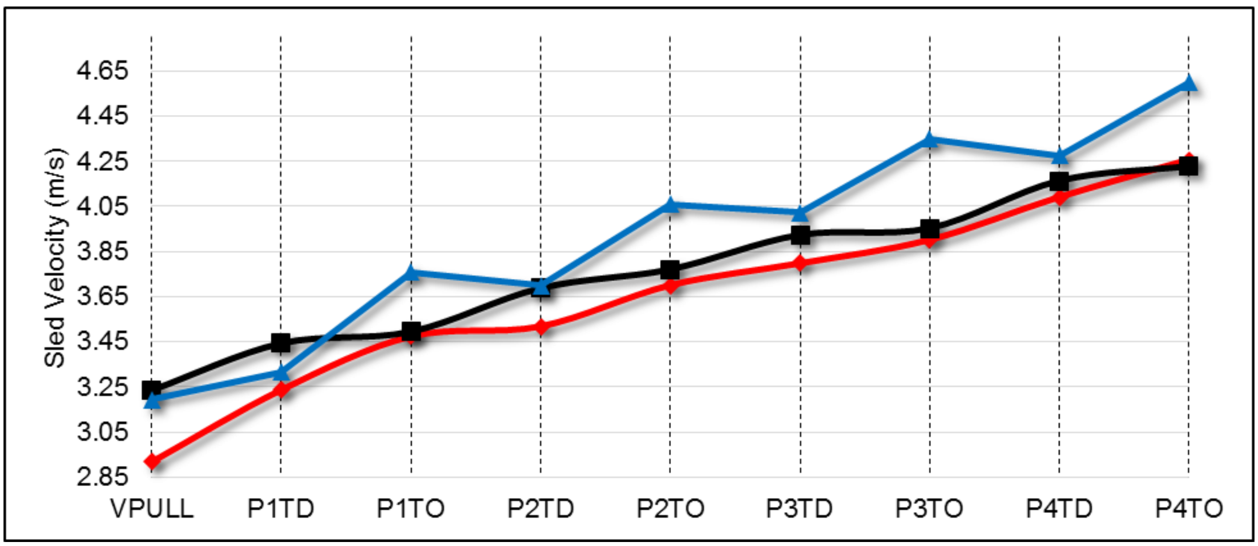


Figure 5-23. Average velocity at different time points (sled velocity at Pull and sled velocity at P_{TD} and P_{TO} from paddle 1 to paddle 4) for subject 1 (red curve), subject 2 (black curve) and subject 5 (blue curve).

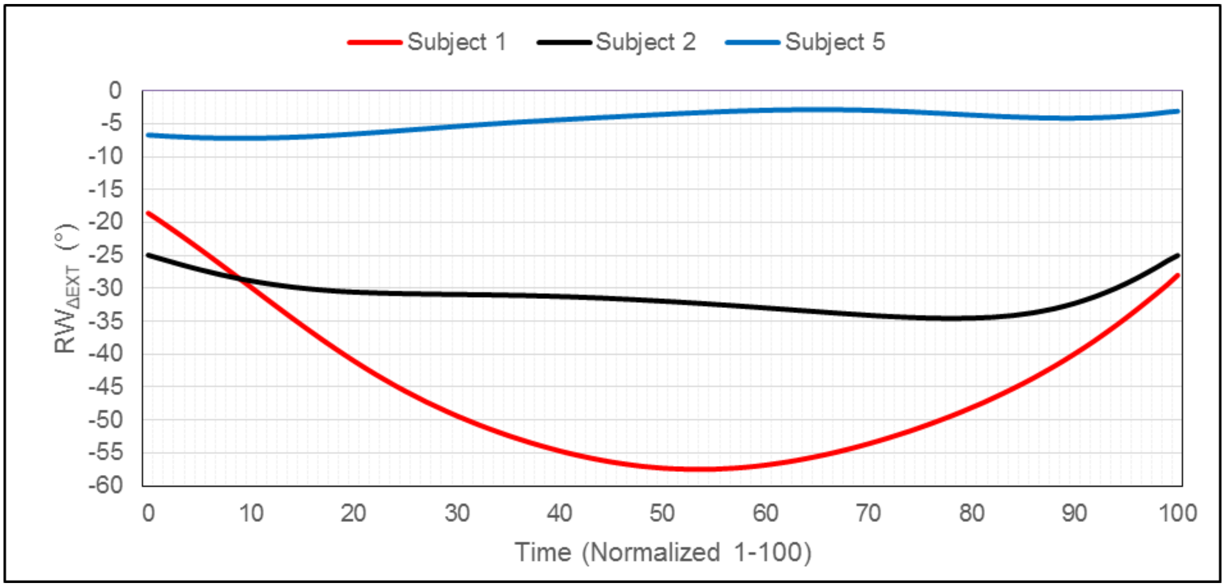


Figure 5-24. Average right wrist joint flexion-extension normalized from P3$_{TD}$ TO P3$_{TO}$, increasing positive values indicate wrist flexion while increasing negative values indicate wrist extension.

On average, female subjects one and five had smaller magnitudes of change in elbow flexion from paddle touchdown to the peak elbow flexion, in particular from P2 to P4. This could be an indication that keeping the elbow joint locked and minimizing elbow flexion has an impact on the paddles.

Table 5-7. Average change in elbow flexion magnitude from P$_{TD}$ to P$_{TO}$ foe left and right elbow joints in female subjects.

Subject	**P1 AVG. EΔ_{FLEX} (°)**	**P2 AVG. EΔ_{FLEX} (°)**	**P3 AVG. EΔ_{FLEX} (°)**	**P4 AVG. EΔ_{FLEX} (°)**
1	22.16	15.88	16.62	21.19
2	22.44	29.93	29.32	24.03
5	20.50	18.23	20.36	18.76

Subject five also showed different trunk kinematics compared to subject 1 and subject 2. Luge athletes are taught to maintain the torso straight and close to the sled as they paddle. Both subject one and two kept the torso relatively in the same position during the contact phase (Figure 5-25). However, subject five extended the torso during the paddle contact phase (Figure 5-25) and toward the final stage of the pulling motion during the paddle.

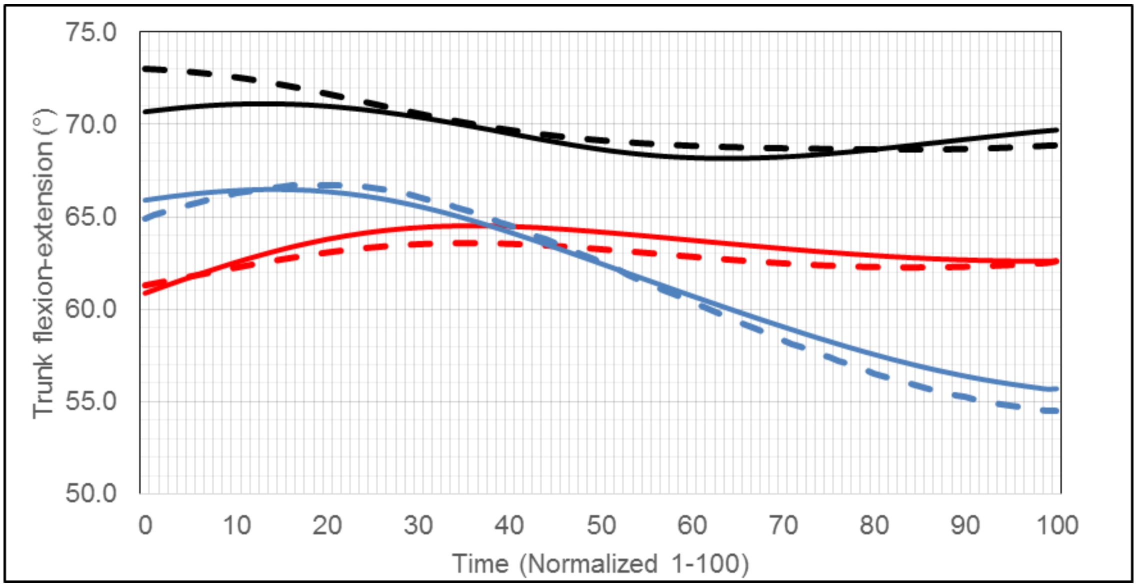


Figure 5-25. Trunk kinematic for female subjects 1 (red curves), subject 2 (black curves) and subject 5 (blue curves) normalized from P_{TD} to P_{TO} for paddle 2 (solid curve) and paddle 3 (dashed curve). Positive increasing values represent trunk flexion while positive decreasing values indicate trunk extension.

For the male subjects, no significant differences in the kinematics could be identified between subject six who increased velocity with the paddles with the rest of the male subjects who accelerated through the swing phase (Figure 5-26). Ultimately, subject seven (Table 5.8) showed the highest average velocity for all of the subjects and gained very little velocity during the paddle contact phase. In a luge competition, the timing system starts measuring at 5-10 meters from the start handles. Whichever mechanics luge athletes adopt will be irrelevant as long as they cover the start phase in the shortest time possible. The two male subjects (4 and 7) who increased velocity during the swing phase had significantly better performances than subject 6 (Table 5.8) who achieved this during the paddle contact phase (overall subject 6 was the slowest of all the male subjects if the laydown was to be considered). Nevertheless, maximizing velocity both through the paddles and swing phases would be optimal for overall start performance.

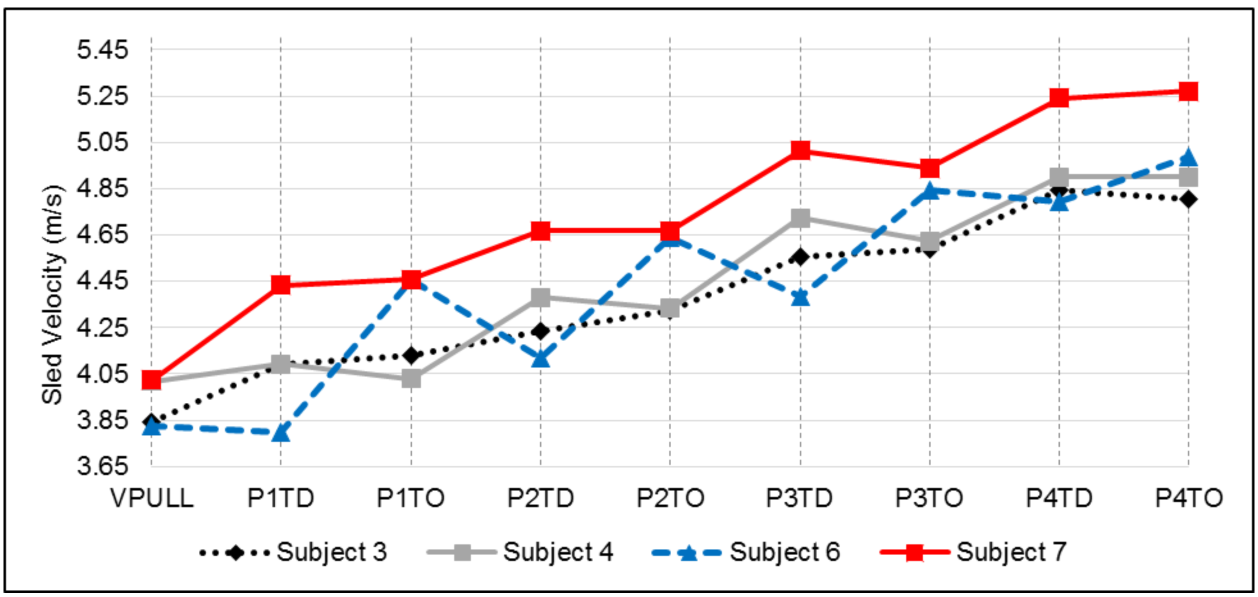


Figure 5-26. Average velocity at different time points (sled velocity maximal velocity at Pull and sled velocity at P_{TD} and P_{TO} from paddle 1 to paddle 4) for male subjects. Subject seven showed the highest average velocity of the four male subjects.

Table 5-8. Performance time based on the auxiliary timing lights and average velocities calculated from the timing lights (Avg. V_{TL}) and motion capture system (Avg. V_{MOCAP}) from $P1_{TD}$ to $P4_{TO}$. Note that the time from the timing lights includes the laydown which occurs after the paddle 4 take-off, and the reason for the highest average velocity from the timing light system.

Subject	**Gender**	**Mass (Kg)**	**Performance time (s)**	**Avg. V_{TL} (m/s)**	**Avg. V_{MOCAP} (m/s)**
1	♀	63.3	2.52	3.58	3.54
2	♀	74.5	2.46	3.66	3.39
3	♂	83.4	2.18	4.13	4.02
4	♂	89	2.12	4.25	4.11
5	♀	57.8	2.45	3.68	3.64
6	♂	73.8	2.26	3.98	4.04
7	♂	89.8	2.04	4.41	4.39

The correlation matrix (Table 5-6) revealed the high influence of the maximal velocity at the Pull (V_{PULL}) with the velocity at Paddle 4 take-off ($P4_{TO}$). Table 5-9 summarizes this result and shows coefficients of determination (r^2) between the velocity points. Approximately 76% of the variance in sled velocity at the paddle 4 take-off velocity is explained by the maximal velocity during the pull phase. Still, it leaves an approximately 24% of unexplained variance that could be attributed to the paddling phase. As it was shown in Chapter 4, the maximal sled velocity achieved during the pull does not necessarily reflect the sled velocity at the release of the handles, in particular for female subjects.

Table 5-9. Summary of Pearson's correlation and r^2 for sled velocity at V_{PULL} with multiple time points of the sled velocity profile.

	$\mathbf{V_{PULL}}$	$\mathbf{P1_{TD}}$	$\mathbf{P1_{TO}}$	$\mathbf{P2_{TD}}$	$\mathbf{P2_{TO}}$	$\mathbf{P3_{TD}}$	$\mathbf{P3_{TO}}$	$\mathbf{P4_{TD}}$	$\mathbf{P4_{TO}}$
$\mathbf{V_{PULL}}$		0.939	0.863	0.951	0.888	0.940	0.891	0.949	0.873
R2		0.881	0.744	0.905	0.789	0.883	0.794	0.901	0.763

The limitations of the study are centered on sample size and statistical power. Seven subjects were available for data collection, four females and three males. Thus, grouping by gender was performed with a limited amount of data. Individual Olympic sliding sports usually have a limited amount of subjects unlike team sports. Reaching the high performance level in a sport like luge requires years of dedication and preparation from a very young age. Thus, the population of luge athletes present in Canada is fairly limited compared to other winter sports. Factors including injuries and the competition calendar also restricted the number of subjects available for this study.

The considerable high p-values obtained from the statistical test are an indication that the low power achieved is due to the small sample size. For example, for an $n = 20$ and a $r_s = 0.30$, the power consists of 37% (Portney & Watkins, 2009). This calculation serves as an example of the under power of this Chapter as it leaves approximately 63% chance of committing a Type II error (this number could be even higher for some of the statistical tests due to missing data points). Nevertheless, in Chapter 4 significant results were found for multiple statistical tests even with small sample sizes. This could question the influence on performance of the different hypotheses discussed in this Chapter.

It is likely that a successful paddling performance is not attributed to only a certain aspect or kinematic variable but rather a combination of factors that make a luge athlete excel during this phase. Future studies should look into increasing sample size not only for a matter of statistical power but also to include in the analysis multivariate statistical models.

To the author's knowledge, this is the first study of its kind investigating the paddles kinematics and performance during the luge start. Two very different mechanisms have been established with regards to how athletes accelerate to achieve the maximal sled velocity before assuming a racing position and covering the start phase in the shortest possible time. Some luge athletes accelerated with the paddles (contact) and the other athletes increased velocity during the swing phase. It is speculated that technique that they use to increase velocity seems to be related to the body mass of the athlete. For future directions, a comprehensive analysis of physiological, anthropometric and strength variables is recommended to further explore these questions

It would be interesting for future studies to look into a kinetic approach of the paddles to understand the interaction of the forces exerted on the ice and impulses with the sled horizontal velocity and the technical execution. Moreover, the sled-athlete interaction and influence of the lower body kinematics (leg kinematics) on paddling performance should be investigated in the future.

5.5 Conclusion

The goal of this chapter was to investigate kinematic factors associated with paddling performance during the luge start. None of the kinematic variables hypothesized showed significant statistical results with the outcome variables. One of the reasons could be associated with the low power of the study due to the small sample size.

Nevertheless, new insights have been brought forth on how luge athletes achieve higher velocities during the paddling phase. The ability to accelerate during the contact phase or by the forward swing of the arms seems to be related to body mass. For this reason, future studies should perform a comprehensive analysis including physiological, biomechanical and anthropometric factors.

Male subjects who increased their sled velocity through the swing phase had substantially better performance than the male subject who achieved this with the paddles. Opposite to this, the female subjects who increased their velocity with the paddles represented a better performance.

The results from this Chapter serve as a reference and created a database of normative data for future studies with respect to the kinematics of the paddling phase in the sport of luge. Similar to the results from Chapter 4, different coaching strategies could be applied based on the gender differences shown in this Chapter.

Chapter Six: **Final Conclusions**

The ultimate goal of this research was to identify key biomechanical performance indicators that were related to the start phase in the sport of luge. The results from this thesis bring new insights to the area of sports biomechanics in the sport of luge. Also, this thesis sets normative data and directions for future studies.

6.1 The use of an accelerometer to evaluate performance on luge start

Having a tool that could accurately measure sled velocity accurately would be crucial to evaluation and monitoring of luge athletes during the off season. Chapter 1 focussed on the validation of a 3D accelerometer to assess continuous sled velocity during luge starts on flat ice. The accelerometer of this make and model was not a valid tool for this purpose. The average RMS relative error was of 5.58% for the four velocity points evaluated. In some circumstances, the sensor could be almost identical as the reference velocity while in other cases the difference was almost 10%.

A systematic error was found in the velocity estimation, as in almost 90% of the trials, the accelerometer underestimated sled velocity. The source of error could be related to the mounting of the accelerometer and misalignment of the device with respect of the sled. If the error was to be related to the misalignment with the luge sled, it could be easily fixed by creating a rigid plastic mounting mechanism that fits between the two runners. Also, incorporating additional timing lights in fixed distance interval could assist in correcting the velocity calculations by taking into consideration the average velocity calculated from the timing system and compare it to the average velocity estimated by the accelerometer.

Different techniques for correcting inaccurate velocities were discussed in the bibliographical review. Some of these methods include a priori knowledge, such as pool length or known distance traveled by the sled. Other approaches involved complex statistical regression models to estimate velocity from an IMU signal. Even though no correction factors were used in this methodology, the results from his Chapter were very similar to what was found in the previous literature.

6.2 Kinetic and kinematic factors associated with pull performance

The pull phase of the start plays a critical role in overall performance in a luge start. In Chapter 5, it was shown that a very high correlation was found between the maximal pull velocity and the velocity at take off in paddle four (r = 0.873). Although the maximal pull velocity does not necessarily represent the velocity of the sled when leaving the handles, this result demonstrates the high influence of the pull phase on the start.

In Chapter 4, it was found that even though all the athletes showed a decrease in velocity from the maximal to the end velocity, a higher maximal velocity did not necessarily represented a higher end velocity at the end of the phase. In particular for females, the end velocity was highly correlated to the relative force being applied on the last part of the movement. Heavier female subjects achieved higher maximal velocities but lighter subjects were able to maintain or minimize the decrease in velocity through to the end of the pull. For the male subjects, the highest predictors with end velocity corresponded to the average relative force and impulse applied during the overall concentric phase of the pull.

These results could have a major impact in the strength and conditioning aspect of luge athletes. It is imperative that increases in body mass are concurrent with strength and power.

Also, because of the apparent relationship of certain anthropometric variables with pull performance, the results of this thesis have the potential to impact on talent identification and selection.

6.3 Kinematic factors associated with paddling performance

Chapter 5 of this thesis focused on the paddling phase of the start. Even though the pull maximal velocity highly influences overall start performance, the impact of the paddles should not be underestimated. The female subject who had the highest average velocity (without considering the laydown) exceled at the paddles, yet had a lower pull velocity than other female subjects.

None of the hypotheses discussed in Chapter 5 had an association with paddling performance, or at least how performance was defined for Chapter 5. However, two distinct ways of increasing sled velocity were found. On the one hand, three of the seven subjects achieved higher velocities while in contact with the ice. On the other hand, four of the seven subjects increased sled velocity merely during the forward swing phase of the arms which appeared to be related to an increase in body mass.

Whichever mechanism luge athletes use to increases velocity, what ultimately matters in the luge start is to cover the start ramp in the shortest time possible. The fastest subject in this case increased his velocity during the swing and almost decelerated in the paddles. According to luge coaches, the best starters in best world manage to achieve higher velocities through the swing phase and also while in contact with the ice.

This chapter centered mostly on the upper body kinematics as the upper extremity are the main force and impulse generators. However, luge coaching theory says that the lower body also plays an important role both for the pull and paddling performance. If the athletes do not apply pressure with the feet to the front part of the sled while the last part of the contact phase, then the propulsive forces generated by the upper body are not transferred to the sled resulting in no increases in sled velocity.

It is likely that paddling performance is not attributed to only one factor but a combination of factors that make an athlete perform during this phase. Due to simple size limitations and violation of normality assumption, the statistical analysis for this thesis was limited to univariate analysis and non-parametrical tests. Future studies including bigger and more heterogeneous samples of luge athletes will increase not only the power but the complexity and statistical approach to the data analysis.

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Appendix A

UNIVERSITY OF CALGARY

CENTRE for VIDEO and PERFORMANCE ANALYSIS

Faculty of Kinesiology
www.ucalgary.ca/cvpa

TITLE: Kinematic and kinetic factors related with bobsleigh and luge start performance times of elite bobsleigh and luge athletes

SPONSOR: Centre for Video and Performance Analysis

INVESTIGATORS: Luciano Sebastian Tomaghelli and Larry Katz

This consent form is only part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. If you would like more detail about something mentioned here, or information not included here, please ask. Take the time to read this carefully and to understand any accompanying information. You will receive a copy of this form.

BACKGROUND

It has been scientifically determined the influence of a good performance start time in final performance time in the winter sliding sports. Many studies involve the analysis of several factors influencing performance such as ice temperature, equipment aerodynamics and physiological factors. However, there is no research to the date regarding biomechanical factors related to start performance. This research will focus on the biomechanical factors affecting the athlete's start performance. Understanding this key elements will allow coaches and athletes to focus on those particular factors that ultimately influence performance.

WHAT IS THE PURPOSE OF THE STUDY?

The purpose of this research is to achieve a better understanding on the kinetic and kinematical factors influencing bobsled and luge start performance in elite bobsleigh and luge athletes.

WHAT WOULD I HAVE TO DO?

If you choose to participate in this study, you will have to perform three bobsleigh push starts from the brakeman position or three luge starts. We will ask you to perform each of the trials like if you where in a competition setting. Each trial resembles the usual start testing that you perform as part of your training.

If you choose to participate, reflective markers will be located in several parts of your body, you will be required to wear a custom made vest and belt. Also markers will be placed in your thigh and leg using elastic straps, additional markers will be located in your shoe using double sided tape. While you are performing each of the starts, we will be collecting biomechanical data from your performance.

If we fail to collect data in any of the trials, we will ask you to repeat that trial.

After every trial you will have a two minute period to rest. Once the last trial is completed, we will removed the reflective markers from your body.

If at any time during the study you decide that you no longer wish to participate, you may stop participating immediately.

WHAT ARE THE RISKS?

The risk is the same risk you undertake while doing start testing, there is no additional risk associates will this study.

WILL I BENEFIT IF I TAKE PART?

If you agree to participate in this study we will give you feedback regarding your start performance and potentially identify factors which might help to improve your start performance.

DO I HAVE TO PARTICIPATE?

Participation is voluntary and confidential. You are free to discontinue participation at any time during the study. If you wish to withdraw from the study, please let it to know to the researchers. Also, the researchers can withdraw you from the study at any point if your health is at risk.

If new information becomes available that might affect your willingness to participate in the study, you will be informed as soon as possible.

WILL I BE PAID FOR PARTICIPATING, OR DO I HAVE TO PAY FOR ANYTHING?

Participation in this study is voluntary and free, you will not be receiving money or any other kind of payment to participate in this study. You will not incur in extra costs other that what you would usually spend for coming to a training session at the Ice House in Canada Olympic Park.

WILL MY RECORDS BE KEPT PRIVATE?

Participation is voluntary and confidential. No one except the researcher and supervisor will be allowed to see any of the raw data. The data is to be summarized. We will be have access to your name and data in order to provide you with feedback regarding your start performance. However for presentation and publication of results only group information will be used and will be kept anonymously. The data will be stored encrypted on a secure computer and hard drive and no identifying data is kept electronically.

IF I SUFFER A RESEARCH-RELATED INJURY, WILL I BE COMPENSATED?

In the event that you suffer injury as a result of participating in this research, no compensation will be provided to you by the Centre for Video and Performance Analysis, the University of Calgary, the Calgary Health Region or the Researchers. You still have all your legal rights. Nothing said in this consent form alters your right to seek damages.

SIGNATURES

Your signature on this form indicates that you have understood to your satisfaction the information regarding your participation in the research project and agree to participate as a subject. In no way does this waive your legal rights nor release the investigators or involved institutions from their legal and professional responsibilities. You are free to withdraw from the study at any time without jeopardizing your health care. If you have further questions concerning matters related to this research, please contact:

If you have any questions concerning your rights as a possible participant in this research, or research in general, please contact the Chair of the Conjoint Health Research Ethics Board, University of Calgary .

______________________________	______________________________
	Signature and Date
Participant's Name	
______________________________	______________________________
Investigator/Delegate's Name	Signature and Date
______________________________	______________________________
Witness' Name	Signature and Date

The University of Calgary Conjoint Health Research Ethics Board has approved this research study.

A signed copy of this consent form has been given to you to keep for your records and reference.