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Development of a Real-time Performance Measurement System for Sprint Starts

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Development of a Real-time Performance Measurement System for Sprint Starts

by

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Abstract

This thesis is an expansion of a Capstone Project where a set of portable sprint starting blocks that can be used for training was developed. For this thesis, two piezo-electric sensors were implemented in the blocks that transmitted data from each of the sprinter's feet to a micro-controller. The sensors, after a series of impact hammer tests, offered a cost-efficient means of collecting valuable telemetric data during a sprint start, and crucially, were non-intrusive. Majority of the athletes demonstrated a consistent three-peak-force pattern in the data collected which was statistically correlated to qualitative performance scores given by a coach evaluating the start. The correlation helped develop a fuzzy method that estimated a performance score for sprint starts and detected false starts. The need to validate this method also helped produce a definitive coach's sprint start evaluation checklist from the National Coaching Certification Program.

Acknowledgements

I would like to thank my project Supervisor, Dr. R. Brennan, for his guidance and patience during this project. Not only did he provide the funding for this project, but also let me develop the experimentation and test plan which helped me understand the finer details of this project as well as gain a deeper appreciation for time management skills. I also acknowledge Dave Brown for helping with the initial design of the starting blocks.

I would also like to acknowledge Bill Wannop, Keith Toupin, Dr. Darren Stefanyshyn, Andrzej Stano for providing valuable information and technical track and field expertise to this project, and providing tartan surface material for the final design of the blocks. I am also grateful to lab technicians from the Departments of Mechanical and Electrical Engineering, Brandon Ferguson, Christopher Simon, and Robert Thomson for helping us with the intricate circuitry of our sensor module. The design team appreciates all the input the Engineering Machine Shop provided, and Timothy Williams and Larry Trudeau for their skills in manufacturing the final product. I would also like to thank Dr. Tak Fung for his valuable input and help with the statistical analyses conducted in this thesis.

Further to this, I am extremely grateful to Coaches Darcy Cummings and Brenda Van Tighem for their time and commitment to this project. Their input, not only with coaching duties such as evaluating sprint starts and providing performance feedback to athletes, but also helping develop a standardized evaluation checklist with the help of the National Coaching Certification Program (NCCP) was crucial to this study. I am also grateful to the athletes training with these coaches for volunteering to try the blocks and let me collect data from their starts.

This project could not have commenced without Dr. W. Herzog. He spearheaded and funded the initial Capstone Design Project in developing a portable set of starting blocks. This

study and any associated developments on the design of the blocks are expansions on the initial Capstone project, and his expertise in the field of biomechanics and his feedback on the results obtained in this study shone a new light in my understanding of the analyzed data. In addition to Dr. Herzog, Jason Coles, Danielle Coolman, Nikolina Stakic, Colin Szpecht, Trevor Wong and myself were the original team of six who were responsible for developing the original proto-type in the Capstone design phase. Without them, the project again would not have gotten as far as it has now.

Dedication

I would like to dedicate this thesis to my family; without their support, guidance, and love I would not have had the motivation to see this project and thesis through to the end.

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List of Symbols, Abbreviations and Nomenclature

Symbol	Definition
α	Incline angle of Starting Block (°)
β	Angle of Block back plate with ground (°)
θ	Block Hinge angle (°)
V	Voltage (Volts)
t	Time (seconds)
F	Arduino value proportional to Force
ΔF	Arduino value proportion to change in Force
J	Impulse (Ns)
tl1	Time at which first front foot Force peak occurs (ms)
$Fl1_x$	Horizontal component of first front foot force peak
tl2	Time at which second front foot Force peak occurs (ms)
$Fl2_x$	Horizontal component of second front foot force peak
tb1	Time at which first rear or back foot Force peak occurs (ms)
$Fb1_x$	Horizontal component of first rear or back foot force peak

Epigraph

“If you can't be a good example, then you'll just have to be a horrible warning.” - Catherine Aird

Chapter One: Introduction

1.1 Motivation of the Thesis

Current competitive starting blocks in track and field are cumbersome and do not offer much freedom for a sprinter's size and shape. Depending on their complexity and feature-set, they are also quite expensive. These blocks feature a middle member that only allows the foot-rests (pedals) one degree of freedom. As shown in Figure 1, there is no adjustment for width. This poses an issue for larger body build athletes and athletes using prosthetic limbs. A further complaint with traditional starting blocks is their lack of portability. Since many sprinters do not train with clubs at prime locations on a regular basis, starting blocks that can be easily stored and transported are a rare commodity and often idealized.

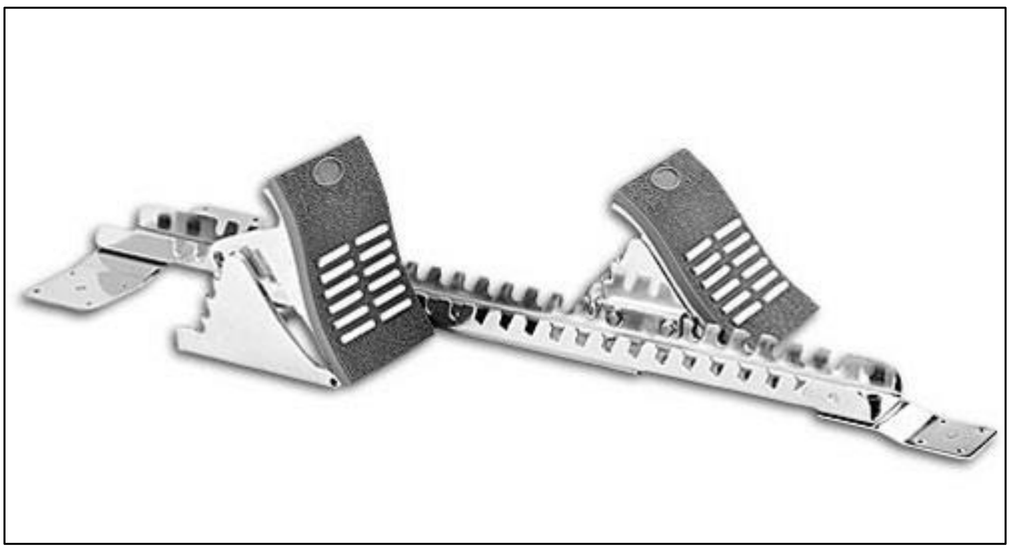

Figure 1: Traditional Starting Blocks

This project is a direct response to the niche posed above and is an expansion on a Department of Mechanical and Manufacturing Engineering Capstone Design Fair project [1] of designing a portable set of sprint starting blocks optimized for personal training. During competitive sprinting events, athletes use a device commonly referred to as "starting blocks", to achieve the quickest start possible. Traditional blocks feature a guide beam with two pedals on either side. This arrangement makes them quite cumbersome and as a result not very efficient for use during personal training sessions. Additionally, there is no adjustment for width which makes them an uncomfortable prospect for athletes of larger builds. With this root-problem in mind, a portable version of the starting blocks specifically optimized for personal training that can be used by a large variety of athletes was engineered.

A version of the starting blocks that were on sale during the early 2000s, called ‘Vers-a-Blocks’ and invented by M65 gold medalist, Dick Richards, featured two independent pedals without a guide beam and proved an excellent source of inspiration for this project due to their highly portable and light-weight design. The Vers-a-Blocks are unfortunately not on sale anymore, and the only information about them that can be publicly accessed is the patent, US6342029.

Unfortunately, the Vers-a-Blocks only solved half the problem. In order to be thoroughly optimized for personal training without the presence of a coach, the blocks should have incorporated a sensor system that could collect and analyze data to provide performance feedback. Further to this, today there is no product in place that collects telemetric data from athletes during sprint starts outside of formal, competitive events. Performance feedback is essential to training as it points athletes in the right direction to better themselves. During group training sessions, coaches are present and routinely provide qualitative feedback on the athletes’ performance and comment on making adjustments to improve. However, this feedback is qualitative and cannot be used for research purposes. For instance, in order to determine exactly why the coach’s qualitative feedback is effective, some quantitative data needs to be collected and compared with the qualitative feedback. If any trends or patterns are observed, then these can be used to further understand the effect of coach feedback during training sessions. Furthermore, a system that can recognize these hypothesized patterns and intelligently provide performance feedback in the absence of a coach would really enhance athlete training sessions.

The initial Capstone Design Project was thus focused on developing a set of starting blocks which are portable, light-weight, and cost effective. The design methodology, design details, design analysis and dimensions were all established during that project. For this thesis, the focus was the development of a sensor system that can collect and analyze data to provide performance feedback to users. No further modifications were made to the design details and justifications because of the added sensor system. [1]

1.2 Organization of the Thesis

The remainder of this thesis is organized as follows: Chapter 2 reviews any related work in the literature, as well as any previous credited work that may be used for this research. Chapter 3 provides a summary of the work done for the Capstone project and how this thesis expands on it, the primary objective, and constraints of this project. It also includes a list of contributions made to the field of study by this project. Chapter 4 offers an overview of the design of the apparatus used for this study, and the various associated challenges and tests to validate the apparatus prior to being used for data collection. In Chapter 5, I review the experimental methodology for the data collection and analysis process along with the assumptions and limitations required for this study. Chapter 6 provides a detailed analysis of the data collected and the subsequent evaluation of said data. Chapter 7 deals with the associated conclusions that can be drawn from this discussion presented in Chapter 6. It also lists the shortcomings of the research and any related future studies that can take place as a result. Finally, a full list of the works cited is provided, along with the appendices.

Chapter Two: Background

2.1 Introduction

This thesis is an expansion of the Capstone project. In that project, a portable model of starting blocks was developed and tested. The starting blocks were a success, but were still incomplete at the end of that project. This thesis aims to address that by outfitting the starting blocks with data collection and evaluation tools so it can help in better analysing the sprint start [1].

To do this, one must understand the mechanics of the sprinter during the three phases of a sprint start: On Your Mark, Set, and Go. Sprinters transition between unique stances in these phases, before pushing themselves out of the blocks in a burst of energy in the "Go" phase. The posture, physical strength, frame of mind, and focus of the sprinter in these stances all contribute to how well the sprinter's start will be. In the same way that a pilot episode determines the success and growth of a new television show, a sprinter's start determines their pace for the rest of the race and can be near impossible to recover from if executed badly.

To examine and quantify the mechanics of the sprinter, researchers have used various techniques and apparatus to model a sprint start as well as record various parameters from a sprinter during a sprint start [2] [3] [4] [5]. In this chapter I start with a review of some of these methods including the use of force plates, two-dimensional and three-dimensional motion capture, and high-speed video capture to compare and contrast with the methods used in this study.

This project primarily involves the collection and evaluation of telemetric data. As mentioned above, one of the motivations of this project is the development of a portable set of starting blocks that are able to collect and evaluate telemetric data. Therefore, it is imperative that this data be evaluated in real-time so that the users can make instant adjustments based on the evaluations. Further to this, the development of an algorithm or program that can intelligently recognize trends and patterns in the data and evaluate it on the spot would be extremely beneficial to this project. Various techniques can thus be detailed under the intelligent control systems umbrella that enables us to develop a program to evaluate the telemetric data. Among these techniques, fuzzy logic is a method that will be used for this study due to its heuristic nature and high synergy to classification type problems.

I conclude with a summary of other designs or ideas for starting blocks and data collection and evaluation from athletes. These designs have been patented in the United States of America (U.S.A.) and as such are novel and not too far-fetched. The reason for discussing these designs is to firstly make readers aware of other similar works done in this area and how this project differs from them; secondly to outline the various shortcomings of these designs either in the way they operate, or functions they cannot fulfil in the field due to the design choices.

2.2 Biomechanics

Due to the specialized nature of this project, no comparable projects were found during an extensive literature review. However, there are many related projects whose results aid in the design of experiments and interpreting the experimental results of this project.

Coh, et al. (2006) focused on the start of just one sprinter – Matic Osovnikar. Two-dimensional 200Hz footage of the start showed key aspects of his sprint start including the block distance, block velocity, low block face/pedal angle, and low vertical rise in total body center of gravity in the first three meters of block acceleration.

In an experimental procedure prescribed by Thelen et al. 2009, use of a force plate to analyze the center of mass and center of pressure for the athlete's feet is proposed. It shows one way to effectively map a two-dimensional map in the x-y plane of the athlete's center of mass in real time. No further records about the applications of this procedures and the associated findings were found during the literature review. Although not directly related to this project, it is worthwhile noting that measuring the amount of force an athlete produces with his or her feet is useful. Similarly, Cross, 1998 noted the various characteristic differences in center of mass movement, velocity, and accelerations during walking, standing, running, and jumping. Findings showed while walking the center of mass follows a curved path rather than a linear one, the centripetal force of which provides an upper limit to the speed at which a person can walk. When running, the findings from this study showed that a person's legs behave like springs and the body center of mass follows the same path as a perfectly elastic bouncing ball. It should be mentioned that this paper also documented the assumption that the test subjects' body weight was split equally between both feet, and the resultant force was a summation of the forces from both feet. While these studies showed the way a sprinter's legs can be modelled while running to better quantify various parameters, it also showed the limitations of force plates; they not only are expensive, but are also not portable. As such, the results of these studies and the apparatus used are both of equal importance to this thesis.

In an entry in the Journal of Biomechanics, F. Kugler et al. 2009 determine the different components of force an athlete exerts on the blocks during a sprint start. Their findings determined that the components largely depend on body posture. An interesting finding from their research was that maximum sprinter propulsion occurs not when the horizontal component of the foot force is maximized, but at an optimum value dependent on body proportions and posture at moment of start. This information is valuable to this research as it helps quantify the qualitative feedback a coach uses to judge and improve an athlete's start during training sessions.

Coh, et al. 2009 also make use of nine high-speed cameras and motion capture to model a sprint start in three dimensions. Their analysis shows that the front foot block takes approximately 66% of the total impulse exerted by the athlete during a sprint start. This is crucial information, since it can be used to validate a coach's qualitative feedback by focusing on the athlete's front foot rather than other areas. Similarly, Coh, et al. 1998 describes the relation between the start-position and the actual force of a sprint start, but in a two-dimensional plane. The paper was focused on finding the relation between various parameters such as push-off force, sprinter launch angle, knee and ankle angles in the "set" position, and so on and the overall acceleration during the first 30 meters of a sprint. The paper confirmed that the horizontal starting velocity, start reaction time, and the impulse push-off force from the front foot only showed the strongest correlation to athlete acceleration during the first 30 meters of a sprint.

Investigations have also been conducted on whether the separation distance between the blocks have an effect on the sprint start. Slawinski, et al. 2012 analyzed the starts of nine sprinters with 250Hz high-speed and motion-capture cameras. The blocks were set at three different distances as a function of the sprinter's height and gait. The results showed that the elongated start (blocks farthest apart in length) consistently showed the highest initial center of mass velocity for the sprinters, but a decrease in performance at the 5 meter and 10 meter marks. This was due to the greater amount of time and effort required to push off the blocks in the elongated set-up. The elongated set-up also showed the highest head-trunk area kinetic energy for each sprinter during the start phase. However, the limited sample size works against this study on forming universal conclusions on this subject.

Differences in sex and the implications on a sprint start have also been analyzed by Ashton-Miller et al. in a PLoS ONE 2011 paper. Before discussing the findings of this paper, it must be stated that the International Association of Athletics Federation defines a false start as "a false start was considered to occur when the increase in force applied by the sprinter to the starting blocks exceeded a given increase in force (i.e. 'threshold') before 100 ms has elapsed from the start gun. [2] [5]" This paper focused on the reaction times of male and female athletes at the Beijing Olympics, particularly with respect to the false start threshold set for the athletes. Unfortunately, the paper did not detail information on the threshold force definition in the Olympic Reaction Time sensing equipment, nor did it contain information about the sensors that the starting blocks were outfitted with to collect the data. The findings listed that any force or change in body posture recorded within 100 milliseconds of the starting gun being fired makes the start a false start. The reaction times of males and females were very similar, however, due to the lower muscle strength in female athletes, the minimum force threshold required for a false start had to be reduced by 22%. This is extremely useful information as it introduces a bias when evaluating male and female sprinters. It also introduces the problem of false start detection and asks whether the current criteria for measuring false starts is unrefined. The possibility of having different criteria for false starts based on sex and indeed body-type is the parting thought invoked by this paper; a thought that this thesis aims to address based on the collected data and fuzzy-logic algorithm.

In a 1997 publication of Sports Med., Harland and Steele [6] outlined the optimal body posture of a sprint start. They showed via theoretical analysis that the sprinter must project himself or herself at a low angle (approximately 40 to 45 degrees) from the ground in the forward direction. A sprinter must also move their body center of gravity ahead of both feet with their first steps out of the blocks for optimal acceleration. These prescribed angles seemed to produce the highest horizontal component of push off force on the front foot, assuming the first or second steps out of the blocks are not impeded in any way. The mathematical analysis presented in this paper will help in correlating the data obtained from the starting block sensors to the stance and posture of the sprinters when exiting the blocks.

A few studies conducted at the University of Auckland described how various loading schemes affected the amount of force generated by the athletes' feet. Although, not directly related to this project, the findings from these studies might help in detailing any expansions on the findings of this thesis. Maulder, et al. 2006 described the various jumping techniques such as countermovement jump (CMJ) and squat jump (SJ), and their effects on leg strength on male sprinters. The paper showed that the ability to generate power elastically during CMJ and concentrically during SJ directly co-relate to each other, and are directly related to sprint start performance over the first 10 meters of sprinting distance. In another study, Hunter, et al. 2005 used thirty-six sprinters to perform sprint starts under high-speed surveillance and on force plates that recorded the athletes' sagittal plane and ground reaction force data, to show the relation between ground reaction force or propulsion force and the acceleration of the sprinter. Linear regression between the sprinter's velocity in the acceleration phase, and the horizontal component of the impulse on the blocks showcased a regression co-efficient of 0.61. Conversely, propulsion force or impulse in the vertical direction varies with foot placement and thus its relation is less conclusive. Lastly, Maulder, et al. 1992 demonstrated the effects of varying resistive loads on a sprint start. Ten male sprinters were used to perform twelve starts each, out of which eight were performed with resistance as a function of the sprinter's body mass. Four of the starts were under 10% body mass load, and four were performed with 20% body mass load.

Two dimensional 250Hz footage of the starts showed that the higher the resistive load, the longer the sprinter stayed in the blocks. However, a resistive load of 10% body mass showed no negative impact on the sprint start. Loads higher than 20% body mass also caused sprinters to shorten their first few strides. The collective results from these papers show the impact of the force exerted by a sprinter's feet on their acceleration. Since this thesis revolves around measuring forces from the sprinter's feet, these studies are vital sources of information on which components of force and impulse from sprinters should be focused on to determine the criteria for evaluating sprint starts.

Miller, et al. 2012 show the relationship between propulsion force and maximum sprinting speed in a computer simulated environment. The study used a two-dimensional model in the sagittal plane with nine rigid segments (trunk, bilateral thighs, shanks, feet, and toes) actuated by 18 Hill-based muscle models (bilateral iliopsoas, glutei, vasti, biceps femoris (shorthead), tibialis anterior, soleus, rectus femoris, hamstrings, and gastrocnemius. The simulation reported that manipulation of the force produced by the fast twitch muscle fibers produced the maximum horizontal speed for athletes. However, since this paper did not use real data to generate conclusions, its relevance to this project is minimal.

Finally, a paper written by a retired Russian professional sprinter, E. Ozolin, 1986 shows the various intricacies of a sprint start, and the optimal postures and angles of various joints during the phases of a start, along with their justifications. The findings presented in this paper appear to be based purely on observational data from an unspecified number of track athletes as no citations or experimental methodology are provided. This information is useful in correlating the quantitative data and the qualitative data collected for this thesis as discussed in Chapter 5.

2.3 Intelligent Data Catagorization

The nature of this project is collecting and analyzing telemetric data to find any significant trends between qualitative feedback provided by coaches and the collected telemetric data. If patterns exist, and can be analyzed by categorizing and assigning performance scores, then an intelligent algorithm can also be designed to simulate or automate the process.

Artificial Neural Network methods such as Radial-Basis Functions (RBF) and Multi-layer Perceptrons (MLP) are well-proven methods for pattern recognition due to their knowledge based algorithm and their ability to learn [7]. However, their strengths also impose a limitation on these methods; they are knowledge-based rather than rule based. An RBF or MLP will recognize patterns in inputs such as speech or an image and get better at recognizing said patterns the more inputs that are fed to it. It is a feedback system that relies on a reference and the growth of the algorithm with every iteration. When applied to this project, with the telemetric data from the sensors acting as inputs to the MLP and the performance score being the output, this system will provide the best scores to later sets of telemetric data rather the first few, since it needs to learn the patterns that it is supposed to recognize. This is not very useful by itself since a good scoring system requires a set of rules and standards that remain constant for every trial or dataset.

On the other end of the artificial intelligence method spectrum is the heuristic rule-based algorithm called fuzzy logic [7]. L.A. Zadeh, in his works from 1965 and 1994 [7] [8], he spoke about fuzzy set theory and the computational applications of fuzzy logic. Fuzzy set theory incorporates the use of various sets or rules, graphically represented as trapezoids between 0 and 1 that contain all the possible outcomes to a given problem. Finding the right outcome in these sets, and then 'defuzzyfying' the value to obtain the true result mathematically enables programmers to accommodate cases that are not just true or just false but can fall in between. This technique therefore is extremely useful in this project to categorize various sprint starts and evaluate the performance for the sprint score.

Lin et al. (1991) presented a neural-network (connectionist) model for fuzzy logic control and decision-making systems. This proposed algorithm combined both unsupervised and supervised learning schemes so that learning speeds converged much faster than classic back-propogation. This was a unique way to solve complex decision making computational problems.

An expert-system problem is one of the applications of fuzzy logic presented by Zimmerman (1993). An expert system is a computer system that emulates the decision-making ability of a human expert. The system is based on various conditional rules rather than conventional procedural code. As such, they can be used as solutions to problems that have qualitative data as inputs [9]. While expert systems excel in solving decision-making problems, it can be argued that their strength can also be their inherent shortcoming. Expert systems, by design, require a large amount of data collected from various experts to form their knowledge base upon which the conditional rules will be formulated. If the knowledge base is sparse, or heavily biased towards only certain decisions, then the expert system will reflect that in its decisions as well [9]. Based on this information it is evident that since Fuzzy Set Theory is a heuristic algorithm, implementing expert-system rules into this algorithm would enable users to tackle data categorization problems.

Chen, et al. (1992) presented the application of fuzzy set theory to Multiple Attribute Decision Making such as aggregation of performance scores for each alternative and rank ordering according to aggregate scores. This was a novel idea and further showed the versatility of the tool L. A. Zadeh had proposed in 1965.

Applications where multiple sensor inputs are required and how to process their signals in an intelligent way via algorithms such as neural networks, fuzzy logic, fuzzy-neural networks among others were presented recently by Klein (2014). This book, although not directly pertaining to this project, shows that even with multiple inputs, fuzzy logic can be used to process an intelligent output based on user-defined rules.

Hybrid systems such as neuro-fuzzy systems have also been successfully used to assess biometric systems like facial recognition, swarm intelligence, speech recognition and other biometrics (Shukla et al. (2010)). The theory presented is very complex, and much deeper than what is used in this project; however, it shows that even complex problems can be tackled with fuzzy logic based algorithms.

2.4 Patent Review

In this section, I review a list of patents that display similar designs to the apparatus used for this thesis and describe how they are different to our apparatus.

Patent US6342029 details the design of the Vers-a-Blocks. The blocks feature two independent pedals with a guide beam. In place of a locking hinge, it features a slider-screw mechanism to lock the blocks in a particular setup for starting. The slider-screw mechanism enables the blocks to fold flat for easy transport; and, as there are no ratcheting gears involved, softer materials such as aluminum can be used to reduce the weight of the blocks. However, the spikes on the blocks cannot be replaced easily, as per design. Consequently, heavily used blocks will need to be sent back to the manufacturer for repair. Furthermore, there is no room to implement a sensor to collect data from the blocks. Thus, the utility of these blocks is limited to support only and the design does not easily enable force data acquisition or feedback. These blocks are designed for training and ease of transportation. However, the presence of a coach is required to evaluate the starting performance while these blocks are used.

Patent US6002336 A describes a modular reaction time measurement system that uses accelerometers mounted on the back of traditional starting blocks to estimate athlete reaction times. Although accelerometers are very good at detecting false starts due to their high sensitivity, this setup principally relies on movement as an input. Accelerometers detect movement and thus work better when the blocks they are mounted to move; even by a very small amount. Despite the lack of documented evidence, it must be stated that this is not ideal as the system relies on induced instability in the blocks at the moment the sprinter pushes on them thus making the sprinter less confident in pushing with full force and having the best start possible. A system that measures forces rather than acceleration would work better in detecting reaction time purely because it does not induce an instability in the blocks during high-impulse starts.

Patent US5467652 A details an apparatus used to measure pressure from an athletes' feet and is an attachment to traditional starting blocks. The main purpose of this device is to optimize training sessions by collecting telemetric data during sprint starts. It measures the amount of time elapsed from the starting gun to the moment maximum pressure is exerted on the blocks. This system is a better means of measuring reaction time than the one mentioned above, however it too is limited in its uses. For instance, despite it measuring pressure peaks independently on each foot and analyzing the data for a suspect false start, it assumes that the definition of reaction time is the time from the starting signal to the moment the sprinter exerts maximum pressure on the blocks. This can be an issue because, as we will see in Chapter 7, sprinters "flinch" a significant amount of time before the maximum pressure is exerted on the blocks. Another observation made in Chapter 7 also discredits this idea since sprinters consistently show two maximum pressure peaks on their front foot.

Chapa, et al. (2011, 2012, 2013, 2015) also describe a performance rating system for athletes based on standardized drills. While analysing drills is beyond the scope of this thesis, it shows the importance and need for a performance rating and feedback system in the field of athletics. Similarly, Nike Inc. with the help of Chapa, et al. registered various ideas with the US Patent office detailing a procedure for measuring and assessing athletic performance which athletes can use to better themselves. The procedures pertain primarily to personal fitness training but show another example of how a performance feedback system could be incorporated into personal training sessions; be it in sprinting or other forms of athletics.

Ashton-Miller, et al. 2014 describe a neurological testing device to measure a human subject's reaction time. The purpose of this is to assess the effects a concussion or other sports related injuries have on human reaction times. It also served to determine and define the various components of reaction time; pre-motor time – from the onset of stimulus to the onset of increased myoelectric activity, electromechanical delay – from the depolarization of the response musculature to the acceleration of the response limb, movement time – from the initial acceleration of the response limb to the completion of the task. While this is a very accurate means of measuring reaction time, it is intrusive in that the athletes must wear a device or harness that might impede their movement and thus their performance during the data collection. A non-intrusive version of this device would be a better apparatus for the application of performance feedback systems in athletics.

Patent US8992386 B2 details a starting block design that measures reaction time via an embedded sensor in one of the blocks. The sensor type proposed is a simple binary switch that closes when 28 kilogram-force is applied by sprinters thus measuring the reaction time as the amount of time the switch was open. The issue with this design is that it is not very accurate in that it does not take into account external factors. If an athlete decides to perform a trial run or step into the blocks to judge comfort level for their start, the switch might close thus compromising the system. Furthermore, since the system is binary, it does not measure an analog quantity of force which makes the device not optimized for applications involving the collection and analysis of force, acceleration, velocity, and impulse data from athletes.

Finally, Patent US20040132559 A1 describes an athletic training device that features pressure sensors that detect when objects have been removed from the sensor pad. These sensors along with an associated microcontroller measure the amount of time elapsed between a starting signal and the objects being removed to estimate reaction times. This system is not exclusive to sprinting and relies on training athletes to improve their reaction times by placing their hands on the sensor pads. However, this system can easily be adapted to sprinting with the sensors mounted in the starting blocks. However, a similar shortcoming exists with this design as with the patent mentioned above – the system is binary. As such, it is not well suited to intelligent performance evaluation.

On top of all the issues and shortcomings mentioned above, the patents also share a common feature – almost none of them make any mention of portability or show any promises as a portable setup designed for athletes to carry with them rather than for track organizations to store in their equipment storage. As a result, the research being undertaken as part of this thesis is the first of its kind and fills not just one, but several niches in the field – a design for portable starting blocks, proposed performance measurement and evaluation system, and the reconciliation of the data obtained from this apparatus with the findings presented in literature.

Chapter Three: Problem Description

3.1 Introduction

This thesis is an expansion on the original Capstone Design project, which involved developing a set of portable sprint starting blocks. Based on feedback received in 2013 from Dr. W. Herzog who sponsored the original Capstone Design Project, a Masters' level athlete who usually trains alone and three University of Calgary Varsity Coaches, a list of the requirements is shown below [1]:

Table 1: List of product requirements based on demographic feedback

Must Have	• Pedals must have an adjustable incline to suit varying body-types • Pedals must provide sufficient traction to not slip during usage • Product collapsible into a medium-sized gym bag
Should Have	• Usable over multiple track surfaces, both indoor and outdoor • Pedals independent of each other • Exchangeable spikes based on track-surface, and to compensate for wear (5mm – 7mm range most common for tracks; typically pyramid or cone shaped) • Durable, long lasting foot-padding • Basic design to be sold for less than $50 CDN
Could Have	• Sensor to detect false-starts and record telemetry data • Sensors for calculation of the left and right foot push off forces and impulses • Upgraded version with false start feature and force measurement

Table 2 further highlights the requirements of the project, and their associated metrics. These metrics helped analyze each need and associate a quantitative value for future specifications. The purpose of this Needs-Metrics Matrix was to quickly identify the design solution of a root problem that emerged either due to a customer requirement or a constraint, and was developed based on the design constraints and customer requirements listed in Table 1.

The metrics are listed as column headers, while the product needs and requirements are the row headers. The dots placed across the grid mark the intersection point between need and metric i.e. the dot represents which specific need(s) are satisfied by a particular metric(s).

Table 2: Needs-Metric Matrix

	METRIC (UNIT)) / NEED	Total size	Total mass	Resisting forces counter-act starting force	Incline can be adjusted in radial increments	Compatible in all indoor and outdoor track surfaces	Foot block width within track lanes	Electronics are encased	Foot block length	Resists 4-5 times average sprinter weight	Spike length cannot surpass competition standards	Special tool required to interchange spikes	Cyclic loading to failure	UV test duration to degrade rubber parts	Yield strength before plastic deformation	Time to disassemble/ assemble for maintenance	Time it takes to detect changes in force output	Output race starting commands	Output force on each block	Reaction time	Unit manufacturing cost	Marketed in North American countries	Retail price	Sensor model price
1	Is portable and compact	•																						
2	Is light weight		•																					
3	Provides sufficient traction to not slip during usage			•																				
4	Adjusts incline				•																			
5	Compatible with multiple track surfaces					•																		
6	Blocks independent of each other						•																	
7	Use during varying weather conditions							•																
8	Adjustable length								•															
9	Block remains rigid during use									•														
10	Interchangeable spikes of different lengths										•	•												
11	Durable foot-padding												•	•										
12	Lifespan 10 seasons												•		•									
13	High wear components replaceable															•								
14	Sensors to detect false starts																•	•						
15	Record telemetric data																		•	•				
16	Must be mass-producible																				•			
17	Commercially available product																					•		
18	Affordable																						•	•

The Capstone project focused on the development of a starting block design that satisfied all of the metrics listed in Table 2. However, due to a tight schedule, the design was sub-optimal and there was room for improvement in various areas. For instance, the original proto-type developed during the Capstone project was no longer functional as it had been disassembled after the conclusion of the project. As such, a new proto-type needed to be made for this thesis. The old proto-type was also too heavy for transport largely due to the 6.35mm thick steel used for fabrication. As such, it was prudent to make the new design lighter to enhance its portability. Therefore, thinner steel (3.175mm) was used in the new model. A stress test was also performed in SolidWorks and ANSYS (see Appendix A) to ensure the thinner steel would not hinder its structural rigidity and risk buckling during high impulse sprint starts. The tests showed promising results, which was further validated by the field testing detailed in Chapter Five.

Another problem with the Capstone design was the sensor system. It was only installed on one of the blocks towards the very end of the project as it was an optional feature in the design (Table 1). Preliminary and brief testing with an impact hammer and a few University of Calgary Dinos athletes proved the sensor design and implementation worked as intended. However, due to the limited amount of time, there was no scientific testing performed to validate the sensor itself and the data collected from the sensor. As a result, further testing on the sensor system was recommended in the Capstone final design report [1].

Lastly, the controller module developed during the Capstone project also required a redesign. Since only one sensor was incorporated into the blocks, the circuitry required to make the sensor communicate safely and accurately with the microcontroller was comprised of a breadboard acting as the bridge between the microcontroller and the electrical components. This made the module an ugly sight that was not portable. A redesign was needed, especially considering for the thesis the plan was to incorporate two sensors (one in each block) rather than one. The program written to test the sensor module featured “Ready”, “Set”, “Go” commands, but also required further optimizations as the delays between these commands were inconsistent with traditional starting command delays during competitive races.

All of the above revisions opened up new avenues to analyze the data collected from the sensors and further the development of the portable starting block system. Therefore, this chapter is dedicated to clearly identifying the objective of this study and the various contributions to different fields of research.

3.2 Objective

As mentioned above, the prototype at the end of the Capstone project needed further development. Furthermore, for the blocks to be truly portable, they must be useful even in the absence of a coach. As such, blocks that could collect data from athletes and provide some performance feedback akin to a coach would enhance their portability even further. The enhancements listed in the previous section enable this goal to be achieved. To this end, establishing a relation between quantitative data collected during a sprint start and the qualitative performance feedback from a coach is imperative and to accurately define this goal, there are many variables to consider.

Firstly, since the portable sprint starting blocks are a proto-type model, the opinion of the athletes is very important and if they dislike the blocks or find a fundamental issue with their design, this study will need to return to the drawing board. Another variable to address is the data collected from the sensors. The data collected from the sensors needs to be comprehensible and more importantly, must be consistent with the other studies listed in Chapter 2. Lastly, since this thesis focuses on designing a performance feedback algorithm that enhances the portability of the starting blocks, finding a correlation or trend between the data from the blocks and the coach feedback is a key objective. With these objectives in mind, the following section details the definitive contributions of this thesis to the fields of engineering design and kinesiology.

3.3 Contributions

This thesis is an expansion of the Capstone Design Project, and thus shares its primary goal of developing a set of portable sprint starting blocks. However, since this thesis is a study about implemented data collection and evaluation tools in the portable starting block design from the Capstone Project, this thesis also has unique contributions to the fields of kinesiology and engineering.

As stated previously, the main objective of this project was to use a set of portable starting blocks to intelligently collect and process quantitative data, thus helping in sprint start evaluations while training. With that in mind, the following is a list of all realized contributions to the fields of engineering and kinesiology:

1. A redesign of the Capstone project portable sprint starting blocks that is lighter due to the thinner steel used in its construction along with a bespoke Arduino microcontroller shield that enables the input from two piezo sensors embedding in the blocks.
2. An updated version of the starting gun command program in the Arduino Microcontroller that features more realistic delays between the starting gun commands, namely, “Ready”, “Set”, and “Go!”.
3. Detailed impact hammer testing and associated results with multiple sensors that was performed in order to select two sensors that output the same voltage for a given input force.

4. Extensive multi-subject study with athletes and coaches that looks into the optimization of sprint starts.
5. Statistical correlation of the qualitative coach performance feedback score and the quantitative data collected from the blocks.
6. Design of a fuzzy filter/algorithm that interprets the data collected from the starting blocks' sensor system and suggests a performance score.

Chapter Four: Apparatus

4.1 Introduction

In order to design a set of portable starting blocks and collect useful data from them, one must first have a detailed analysis and design justifications in place to ensure the proposed design is capable of reliably working the way it was intended to for a large number of a trials. Once the design is finalized along with scientific and monetary design justifications, a proto-type can be made to validate the design. This was where the scope of the Capstone Design Project ended [1].

In this chapter, I start with the origin of the blocks from the conceptual phase during the Capstone Design Project. A mathematical analysis of the dimensions of the blocks and the hinge design is presented as design justification. Although not the focus of this study, a brief description of the material choice for the blocks is also presented.

Next, I detail the focus of this thesis, an expansion to the design of the blocks inherited from the Capstone Design Project, namely, the controller used for this study, and the decisions involved in its design. The controller and the various parts used therein are listed along with their respective limitations. Finally, I conclude this chapter with a section on the sensors chosen to interact with the controller and the associated testing to validate the sensors themselves.

4.2 Starting Block Design

The hardware that I used for this project was a set of custom-designed Portable Sprint Starting Blocks. These blocks were designed to be portable with just two (2) pedals and no central guide-beam [1]. The two pedals feature a ratcheting hinge that enables them to be set to the users' preferences, and then fold back flat to stow away. This was key as one of the primary goals of this project was to produce a marketable product (pictures provided in Appendix A).

Following a thorough series of calculations shown below involving geometry, trigonometry, and engineering statics (Appendix B) during the Capstone Design phase of the project, the optimal dimensions for the blocks were determined (Table 3). These dimensions and the overall design were adopted for this project as well. However, the design had to be reproduced since the original prototype from Capstone Design phase had already been dis-assembled and the sensor system was no longer functional. For the reproduction, the blocks were lightened by using thinner steel (3.175mm) rather than 6.35mm thick steel in the Capstone Project, and having structural reinforcement in the most vulnerable locations such as across the front plate and the hinge.

Table 3: Sprint Starting Block Dimension Justification

Part	Justification
Front Plate	The front plate was set to 140mm x 140mm area to accommodate for any athlete's shoe size. In order to have an optimal start, it is preferred to have at least 2/3rd the athlete's foot in contact with the starting block. The thickness is set to 3.175mm. to accommodate for the available stainless steel sheet thickness, and to ensure the blocks remain light weight.
Back Frame	The height of the back frame is set to 203.2mm so the incline of the front plate can be adjusted from 30° to 75° (measured from the ground/horizontal to the plate).
Shaft	The shaft is the component that attaches the two socket wrenches together. Ideally the shaft would have a hollow rectangular hole all throughout to reduce the weight. The shaft ensures symmetry of the blocks.
Socket Wrench	The socket wrenches have two functions: one is the ability to change the incline and the latter is a locking mechanism ensuring safety that the blocks will not collapse during use.
Spike Plate	The thickness is set to 3.175mm in order to provide weight support and enough depth for the spikes to be threaded in at the bottom.
Spikes	Dimensions of spikes change with changing track surfaces, and are thus fixed by a standard for each surface. Therefore, spikes for outdoor surfaces are longer and wider than spikes for indoor surfaces.
Tartan / Foot Padding Surface	The tartan surface is 25.4mm smaller in width and height of the front plate (12.7mm off each side) so that it doesn't easily damage/ peel off. The tartan has to be a thicker than the spikes so that it doesn't damage the front plate and the sensor.

It is evident from these calculations (Appendix B) that with the spikes in the ground, these blocks have very little means of sliding under impulse. The only instability that can occur is if the blocks tip over. This would cause the blocks to rotate about the spikes in the back plate. As such, an optimal length for the back-frame will counteract this tipping by allowing the line-of-action of the sprinter's forces to pass below the spikes in the back plate, as shown below:

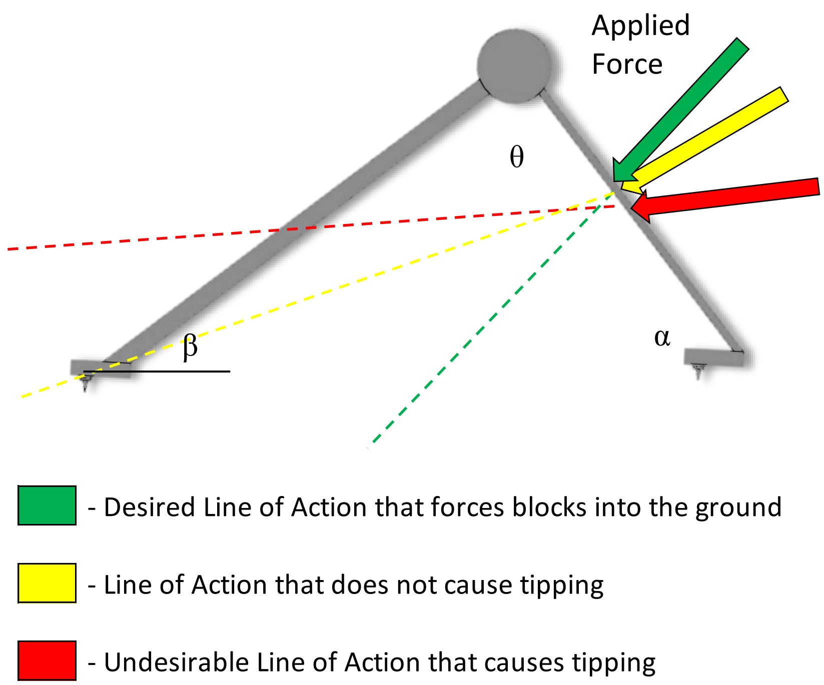

Figure 2: How applied forces can cause the blocks to tip over

In Figure 2 the red arrow and line represent the least desirable force and line of action as it passes above the axis of rotation thus creating a positive, counter-clockwise moment which would cause the blocks to tip over. The yellow arrow represents a more desirable line of action as it passes through the axis of rotation at the back-plate spikes. Similar to how pushing a door towards its hinge doesn't cause any rotation, the yellow line of action will not cause the blocks to tip over. However, controlling this is very difficult as sprinters vary in height, weight and thus will naturally apply different forces and line of actions on the blocks. As such, the most desirable line of action, represented in figure 2 by the green arrow, shows that the force applied by sprinters will not tip over the blocks but will in fact drive the blocks into the track thus increasing their stability and encouraging more explosive starts. Naturally, a heavier athlete or an athlete who places his or her feet higher up the blocks will cause the blocks to tip over more easily. A mathematical model for a starting block can be derived to illustrate the problem of tipping based on the free body diagram illustrated below:

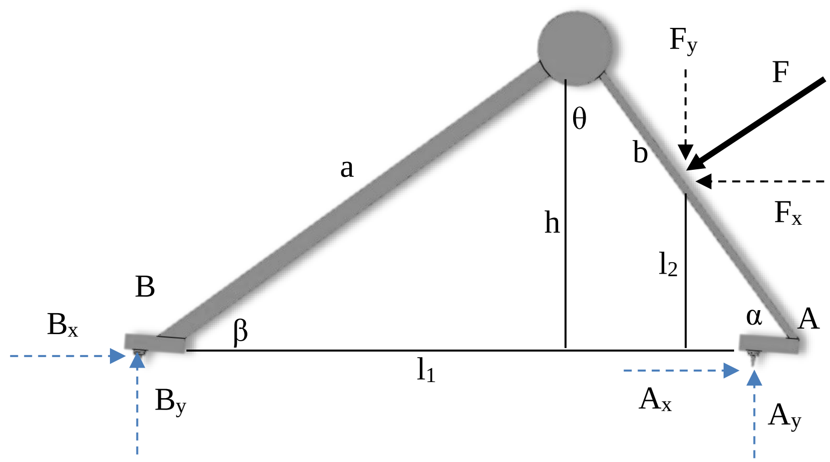

Figure 3: Free Body Diagram of starting block with input and ground reaction forces

In figure 3, Points A and B = points of contact between the blocks and the ground

a and b = segments describing the front and back plates of the block

h = vertical height of the block

l_1 = horizontal distance between points A and B

α = incline angle of the block, between the front plate and the ground

β = angle made by the back plate of the block and ground at point B

θ = angles made at the hinge of the block between the front and back plates

F = input force from athlete's foot on the block's front plate

F_x and F_y = x and y components of the input Force

A_x and A_y = ground reaction forces in x and y directions at point A

B_x and B_y = ground reaction forces in x and y directions at point B

l_2 = height at which the force, F is applied on the front plate

Firstly, based on the free-body diagram of the starting block above, the mechanical equations governing a desired static system are as follows:

$$A_y + B_y - F_y = 0$$

$$F_x - A_x - B_x = 0$$

Since we want the blocks to remain stationary and not tip over or rotate about point B, the moment about point B can be modelled as follows:

$$\sum M_b = 0$$

$$\therefore A_y l_1 + F_x l_2 - F_y l_1 = 0$$

$$\therefore A_y l_1 + F_x l_2 = F_y l_1$$

Where,

$$F_x = F \sin\alpha$$

$$F_y = F \cos\alpha$$

Applying the sine-law to the block's geometry:

$$\frac{\sin\theta}{l_1} = \frac{\sin\alpha}{a} = \frac{\sin\beta}{b}$$

$$\therefore \sin\alpha = \frac{a\sin\theta}{l_1}$$

$$\therefore \sin\beta = \frac{b\sin\theta}{l_1}$$

Now, at the instant the block pivots or is about to tip over, the ground reaction force at point A are nullified. Thus,

$$\therefore F_y = B_y$$

$$\therefore F_x l_2 = F_y l_1$$

$$\therefore F_x = F_y \frac{l_1}{l_2} = A_x + B_x$$

From the definitions of F_x and F_y and the sine law above, it can be stated that,

$$F_x = F\sin\alpha$$

$$F_y = F\cos\alpha$$

$$\sin\alpha = \frac{a\sin\theta}{l_1}$$

$$\therefore F_x = \frac{Fa\sin\theta}{l_1}$$

Thus, a mathematical relation defining the length of the back plate and the input force can be written as,

$$\therefore F = F_x \frac{1}{a}\frac{1}{\sin\theta} l_1$$

Or,

$$\boxed{\therefore a = \frac{F_x}{F}\frac{1}{\sin\theta} l_1}$$

Therefore, it can be seen that the length of the back plate is inversely proportional to the input force and the hinge angle of the starting block. If the vertical component of the input force is just the athlete's weight, then each block will only be exposed to half of it assuming an even weight distribution between the athlete's feet. We also know that the hinge angle is dependant on the incline angle, as per the sine law. As such, the length of the back plate for an athlete with a given weight can be calculated and graphed for a variety of incline angles. It must be stated that due to the length of the back plate being dependant on the weight of the athlete, if we design the back plate to remain steady without tipping for an extremely heavy athlete then it will be able to withstand lighter athletes as well. Therefore, if we define the length of the front plate to be 140mm, as stated in Table 3, then for an athlete with a mass of 90 kg, the minimum length of the back plate to avoid tipping as a function of the incline angle is presented in Figure 4. Based on valuable opinions from established athletes and coaches like numerous University of Calgary Dinos [10], figure 4 also shows the average range of incline angles, α used by the majority of sprinters. It is clear sprinters rarely use inclines greater than 60^o. This corresponds to a minimum back frame length of approximately 20cm. This was further validated in Coh, et. al 1998, where they recorded the mean start-push off incline angle for men and women of 49.54° and 53.2°, with standard deviations of 2.91° and 3.2°, respectively [4].

The remaining dimensions such as width and height of the blocks were based on market research on the Vers-a-Blocks and traditional Olympic starting blocks.

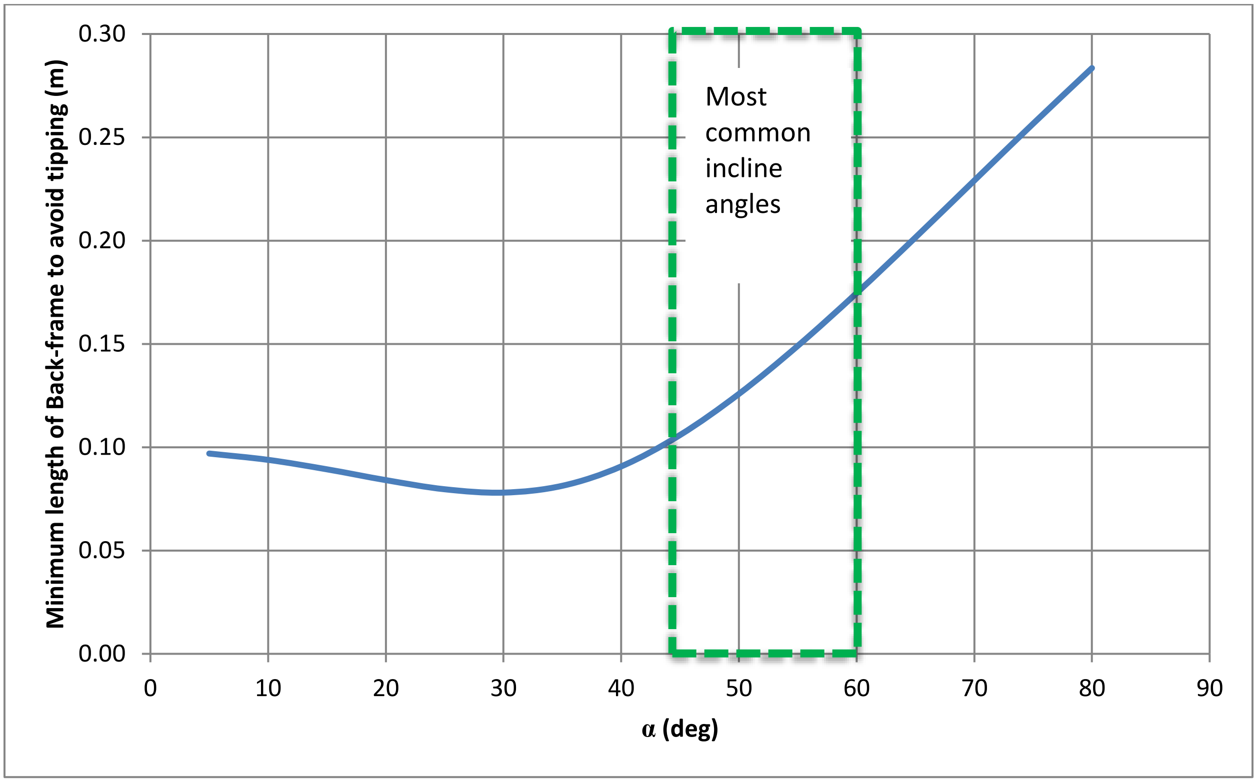

Figure 4: Optimum Length of supporting frame on Starting Block [1]

On the hinge design, when the socket wrenches are inverted (rotated in opposite directions), they lock the starting blocks to the desired incline. When the socket wrenches are locked in the same direction, it allows the user to increase or decrease the incline, depending on the settings. A user manual (Appendix C), was also created to get new users acquainted with the starting blocks and explain how the hinge mechanism and the microcontroller software worked.

This design choice does not completely solve the problem of asymmetry, since at any given time, only one of the socket wrenches is taking the sprinter's load. However, based on the detailed stress-analysis in Appendix B, each socket wrench, rated to a maximum load of 2035Nm, is more than capable of supporting these applied loads, with a maximum calculated load for a 90 kg athlete of 441 Nm.

As mentioned in Chapter 2, accelerometers were already ruled out since they rely on an instability induced in the blocks from the athletes' feet, which can be detrimental to the start. Therefore, other alternatives must be considered to collect the data required for evaluation. The International Association for Athletics Federation (IAAF) also detailed the use of force from the athletes' feet in the official rules for determining a false start [5]. Therefore, a sensor that enabled the measurement of force from the athletes' feet was ideal for this design. A number of sensors were considered for this proto-type [1]:

1. **Strain Gauge** – This was an initial sensor idea but the strain gauge conflicted with the functionality of the blocks. Two or four strain gauges would be configured in a Wheatstone bridge on either side of the front plate, measuring the bending in of the front plate. Many sensor locations were hypothesized but this sensor was not considered in the final design because the functionality of the product is reduced if deflection and bending occurs in our product.
2. **Load Cell –** Similar to the strain gauge idea, a load cell was also considered, with the ideal placement in between where the spikes would make contact with the ground and the front plate. This idea was scrapped because the load cells would mostly measure the force in the vertical direction, and not the horizontal applied force from the sprinter.
3. **Force Sensing Resistor (FSR) –** This sensor is a thin film applied over the entire surface of the front plate. This would have been an ideal candidate initially, but there were several issues with the use of this sensor. Firstly, the commercial sensors can only detect a maximum of 20 N of force which is much too low to comply with the IAAF false start detection rules [5]. Secondly, these sensors are fragile; if the spikes made contact with the film, it would most likely destroy the sensor.

4. **Contact Sensor –** This sensor was considered due to the ease of implementation but was very limited in application. This sensor only registered readings when the force is applied/ removed i.e. a binary system. This would not allow us to measure the true reaction time (the difference between the reaction to the gun and when the foot is removed from the blocks), nor would it provide analog data that can be evaluated.
5. **Piezo-electric disc –** This sensor was the final candidate considered for this design. They feature a piezo-electric crystal that generates a voltage that is proportional to the pressure applied, which is ideal for this application. These sensors, though cost-effective, are very sensitive and are therefore are a viable choice to measure the amount of force the athlete produces over the short duration of a sprint start.

The piezo-electric disc sensors are also fragile and are thus embedded in a 0.635cm thick rubber pad. The sensors and the accompanying leads are held in place with silicone gel. To protect the sensors from the spikes in the sprinting shoes, there is another layer of tartan between the rubber pad and the athlete's feet (Appendix A).

4.3 Micro-Controller Design

Micro-controllers are a very versatile and relatively cost-effective means of collecting electronic data from various types of systems. There are different micro-controllers available in the market for different applications. For example, the Raspberry Pi micro-controller is useful for processor-intensive systems that don't collect sensory data. These mini-computers can stream data from various sources and process it on the board itself without having to rely on an external computer. On the other end of the spectrum are the Arduino micro-controllers. These micro-controllers, while limited in their processing power, can collect analog and digital data from various electronic sensors and send it to a computer for processing and display. Arduinos, due to their C++ interface, are also easy to program with scripted code that can be run for step-by-step style operational problems.

The micro-controller chosen to collect data from the blocks was an Arduino Uno R3. The reason for this was its simple and compact design and its synergy with large variety of analog and digital inputs. This controller has two tasks: output a sequence of beeps via a speaker to simulate the commands during the sprint start, namely “On your marks”, “Set”, and “Go!” and collect force data from the blocks as the sprinters react to these commands. The data for the purposes of this study will be displayed on a computer directly connected to the Arduino. This methodology was developed during the Capstone Design Project [1] (see Appendix D), but was upgraded for this thesis with the implementation of the second piezo sensor.

The Arduino Uno, though, simple and versatile in design also has some limitations. Firstly, the analog pins on the board can only withstand a maximum voltage of 5.0V before being rendered ineffective. As such, the voltage coming in from the piezo-electric sensors would have to be limited in some way in order to not break the Arduino after one use. Secondly, the on-board memory of an Arduino is very small, at 32KB [11]. Thus, this board is only capable of a maximum sampling frequency of 50Hz. Lastly, for this project, the Alternating Current (AC) voltages provided by the Piezo sensors is something that needs to be rectified both for better data analysis and to protect the Arduino circuitry.

Since there are two sensors (one for each block) acting as inputs and a speaker acting as the output, this can be considered a Multi-Input-Single-Output (MISO) system. As such, a custom shield for the Arduino needed to be made to ensure clean connections and no interference between the pins of the Arduino. The shield acted as the interface that the sensors were connected to and housed all the electrical components necessary for the sensors to communicate with the Arduino. For each sensor, the shield consisted of a Zener diode to limit the voltage from the sensor to levels that the Arduino can withstand without issue. Since this thesis involved data evaluation, rather than simply data-collection as in the Capstone Design Project [1], the shield had to be rebuilt with additional circuit components. Namely, a rectifier to convert any AC voltages to DC and an associated resistor-capacitor (RC) circuit (47μF, 1000Ω) to smoothen the DC voltage curve. Finally, a resistor of 2700Ω is also present to complete the circuit (Appendix E). The sensors are connected to a custom designed circuit and Arduino Uno Microcontroller. The rectifier bridge converts the analog AC voltage from the sensors into a DC voltage so all of the data is positive. The RC circuit ensures there is no residual voltage in the circuit after the sensor produces a voltage. This ensures the board is reading the actual voltage on the sensor rather than a cumulative value. (refer to Figure 10 for screen output). For this project an LCD capacitive touch display shield was also added to the controller, however the functionality was not implemented due to time and resource constraints. A second 200Ω resistor is in place on the ground side of the circuit and in conjunction with the RC circuit, it drives any residual voltage in the pin to zero. This ensures that voltage from the sensor circuit is driven to zero volts before the next sample is pulled by the Arduino, at a sampling frequency of 50Hz. This whole circuit is copied for the second sensor. Both are connected to the Arduino as analog inputs since magnitude of the sensor data is important for this research.

In order to simulate a realistic sprint start, the Arduino Uno was also outfitted with a piezo speaker which outputted a sequence of starting commands, in the form of beeps, corresponding to the “On your marks”, “Set”, and “Go!” commands issued during a race. The speaker also alerted the user with a double-beep sound in the event a false start was detected. If the starting sequence is a step-by-step process that is programmed electronically, then athletes can exploit this and anticipate the “Go” command or beep to generate perfect starts every time. To counter this, the Arduino was programmed such that the delay between the “On your marks” and “Set” commands was constant at 10 seconds, but the delay between “Set” and “Go” commands was randomized between a range of 1500ms to 2500ms. This ensured that sprinters could not anticipate the starting gun and exploit the system. [1]

4.4 Sensor Testing

Using piezo-electric discs was an idea formulated during the Capstone Design project. However, due to schedule constraints and the fact that the sensor was not a primary objective of that project, no laboratory testing was done to validate if the piezo sensors were actually the best choice for this job; rather was implemented purely as an illustration of how a sensor system could be designed on a small budget. [1] The piezo-electric discs are extremely sensitive sensors and are prone to detecting ambient noise. Furthermore, due to manufacturing defects or the grade of the piezo element inside the sensor, the probability of multiple sensors having the same sensitivity is very low and this must be verified.

For this experiment ten (10) different sensors were tested in order to find two sensors that gave similar voltage readings to a series of controlled impacts. The apparatus included the sensor, a metal block to brace the sensor to, electric tape, an oscilloscope with alligator clip leads, and an impact hammer (Figure 5). The impact hammer enables us to test the sensor output using controlled, repeatable impacts. The impact hammer model used for this thesis was the Amsler Otto Wolpert-Werke GMBH D6700, manufactured in 1984, and the test was performed in the University of Calgary Mechanics of Materials Laboratory. The main purpose of this test, thus, was to validate consistency; both between multiple sensors, and for each sensor as well with multiple trials.

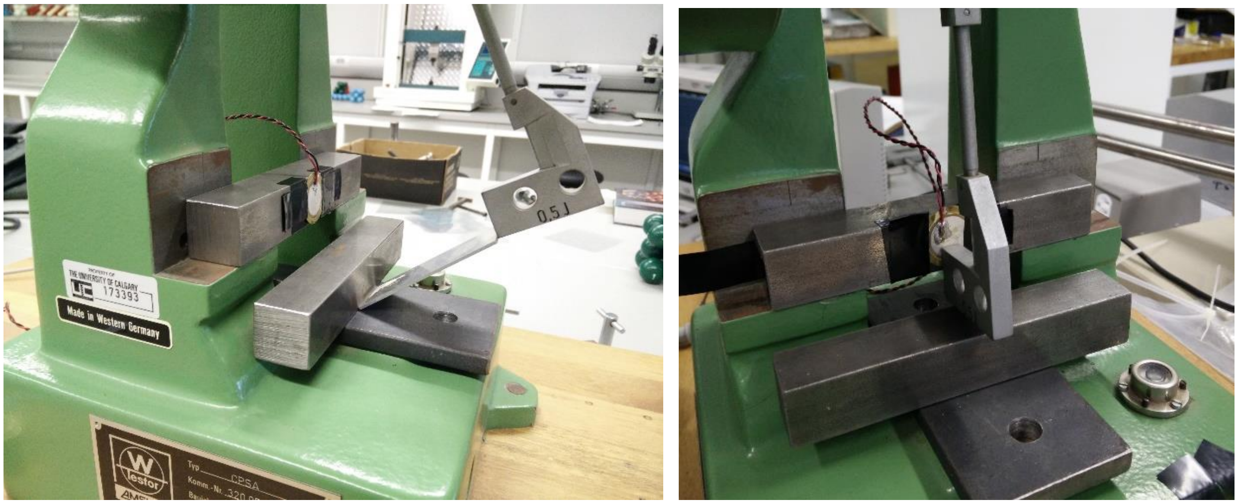

Figure 5: Impact Hammer Machine Sensor Validation Apparatus

The impact hammer is a pendulum with a weighted hammer at the end. This pendulum can be set at any angle from 0^{o} (at the 6:00 position on a clock face), and 180^{o} (at the 12:00 position). The amount of energy the pendulum hammer exerts on any object at the base can be calculated using the known weight of the pendulum hammer, length of the arc the pendulum travelled and the radius of the arc. The pendulum can then be released to produce an impact on any object placed at the 0^{o} position. For this experiment, all the trials were conducted with a starting hammer angle of 27.9^{o}, and at moment of impact, the ending hammer angle was 7.2^{o}. This is due to the metal block offsetting the sensor further forward than right at the base of the circle of rotation of the hammer, as seen in the pictures in Appendix F.

The initial goal was to verify whether the soldered leads on the piezo elements, and if their orientation had any effect on the data collection. Four different sets of trials were conducted; each set had the leads oriented in a different direction (North, and East). The test was merely to confirm if the soldered leads and their orientation affected the voltages produced, and as such only two sensors were used for this test. Due to the impact hammer apparatus itself causing an obstruction, a set of trials with the leads oriented West or South was not performed. The data can be seen in Table 4.

Table 4: Sensor Orientation Oscilloscope Data

Sensor	Orientation of leads	Voltage (V)
1	North	58.0
1	East	80.0
4	North	41.0
4	East	65.0

This test confirmed that sensor orientation affects the data produced by the sensor, however the effect is uniform across all the sensors that were tested. As such, if the sensors used in the Sprint Starting Blocks data collection are oriented the same way, one source of error will be eliminated from this experiment.

The second test with this apparatus was to measure the consistency between sensors. With all the sensors having their leads oriented North, the impact hammer was unleashed on each sensor a minimum of five (5) times. The goal of this experiment was to ensure that for the same force, the sensor gave the same voltage reading repeatedly (Table 5) (refer to raw oscilloscope output in Appendix G). Also, finding two sensors that produced the same voltage reading for the same impact force was required since this would make the readings from the sprinter’s feet more uniform without bias. The acceptance criteria for this test was two standard deviations due to the sensors’ high sensitivity and high rating of over 100V; if the sensors exhibited erratic behavior that was further than two standard deviations from its mean, then that sensor was deemed defective. Likewise, if two sensors produce means within two standard deviations from each other, then those sensors were considered candidates for implementation in the starting blocks.

Table 5: Peak Oscilloscope Sensor Voltage when struck with impact hammer

Sensor	Trial 1 (V)	Trial 2 (V)	Trial 3 (V)	Trial 4 (V)	Trial 5 (V)
1	***58.0***	***58.0***	***59.0***	***58.0***	***58.0***
2	-	66.0	-	71.0	72.0
3	***58.0***	***57.0***	***57.0***	***58.0***	***58.0***
4	52.0	48.0	45.0	41.0	41.0
5	75.0	75.0	75.0	71.0	74.0
6	65.0	65.0	65.0	69.0	65.0
7	64.0	64.0	64.0	64.0	64.0
8	70.0	72.0	69.0	70.0	69.0
9	69.0	69.0	69.0	69.0	69.0
10	75.0	75.0	75.0	75.0	75.0

Based on the data in Table 5, the mean and standard deviation for each sensor can be calculated (Table 6).

Table 6: Mean and Standard Deviation for each sensor from Oscilloscope data

Sensor	Mean	Standard Deviation (+/-)
1	***58.2***	***0.45***
2	69.6	3.21
3	***57.6***	***0.55***
4	45.2	4.72
5	74.0	1.73
6	65.8	1.79
7	64.0	0.00
8	70.0	1.22
9	69.0	0.00
10	75.0	0.00

Results from Sensor Testing (Tables 5 and 6) indicate Sensors 1 and 3 show a very consistent and almost identical impulse responses, and fall within the acceptance criteria of two standard deviations. Both sensors produced consistent voltages for repeated trials with the same force. Furthermore, both were consistent with each other, which implied that both were equally sensitive. Sensors 8 and 9 show a similar behavior as well, however sensor 8 failed the consistency test since one of its readings was over two standard deviations away from the mean.

Chapter Five: Methodology

5.1 Introduction

The experimental methodology for this project is very straight-forward. It involves testing the integrity of the blocks and the sensor system using real athletes, both male and female, of varying height, weight, age, and skill level. The selection of athletes was done using various channels – advertisements, posters, but primarily word of mouth. Having the contact information of some varsity track and field coaches also helped pull in athletes for testing.

Since this research requires human participation, a formal ethics approval process was followed and the necessary permissions were obtained from the University of Calgary Ethics Board, filed under REB14-1780.

The main experiment that is performed is having each athlete perform multiple starts from the blocks at the best of their ability. During these starts, a coach is also present to evaluate the start qualitatively based on what he or she sees, and their experience in the field. The qualitative analysis is then compared and correlated with the quantitative force-time data that is collected from the blocks to draw parallels and enhance the performance feedback. Collecting and evaluating such data is the obvious primary step to accomplishing the research goals.

In this chapter, I detail the way the data was collected and the demographic it was collected from. Important factors such as location, athlete and coach availability, time of year, athlete height, weight, age, sex, and experience all play a role in this research and the first section of this chapter deals with the implications of and the limitations imposed on this study by these factors.

The second section of this chapter focuses on the evaluation of data collected on the track from various athletes. Prior to formulating any computer algorithm, various statistical and graphical correlations were performed on different parameters of the entire sample collected. The patterns observed in these correlations are then discussed in this section.

5.2 Data Collection

The data was collected on both the indoor and outdoor track surfaces depending on prevailing weather conditions. During the colder months, the athletes were training on the indoor track at the Jack Simpson Gymnasium at the University of Calgary, and during the summer the athletes trained at the Foot Hills Outdoor track near the University of Calgary Campus.

Before the data collection commenced, a digital video camera (Sony SLT-A77 II, Sigma 35mm F1.4 lens) was set up on a tripod at the edge of the track lanes to record the start. The starting blocks were set up in lane with the Arduino Uno connected to the computer (Dell XPS 13, 8GB RAM, Intel Core i5-5200U 2.19GHz) and the Arduino Terminal application running. The sprint starting procedure that included the “Ready”, “Set”, “Go” commands and the data collection commands was written in the Arduino Terminal Environment in C++. The athletes were given a briefing about this research, the blocks and their design, along with how the data will be collected. A consent form was also made available for the athletes to sign before they used the blocks, in accordance with the Ethics Approval REB14-1780. For many the starts, one of two coaches were present to provide performance feedback. For any starts that the coaches were not available, the video of the start from the camera proved useful to evaluate the start at a later date. A total of 106 starts were performed, out of which only 103 were evaluated by coaches; since, for three of the starts the video capture equipment was malfunctioning. Furthermore, due to the availability of the athletes during the training sessions, more male athletes were tested than female ones, as seen in Figure 6. The athletes ranged from 16 years, to

26 years of age, with a majority having a left front foot stance when starting. Athlete height and weight were also taken into account (Figure 8).

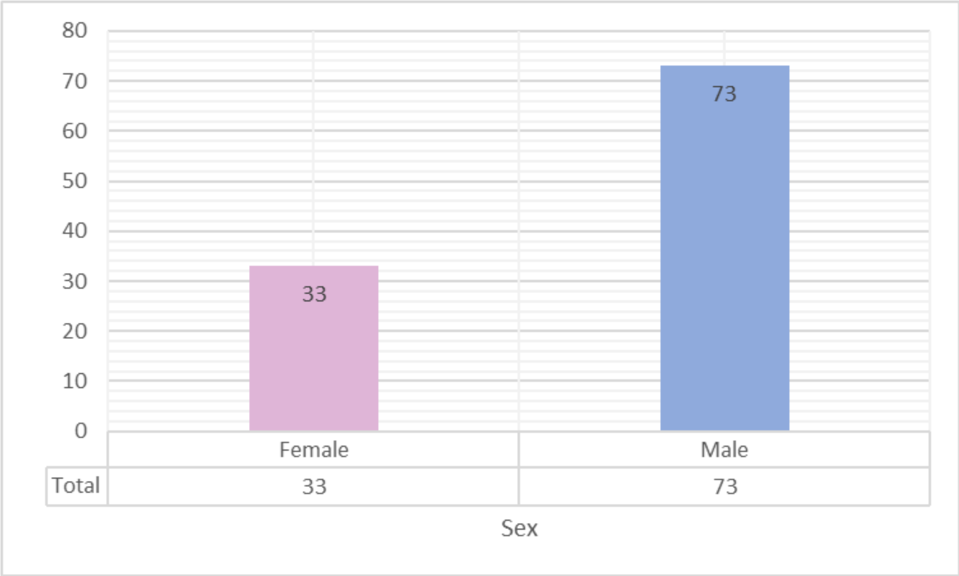

Figure 6: Distribution of Male and Female athlete starts used for Data Collection

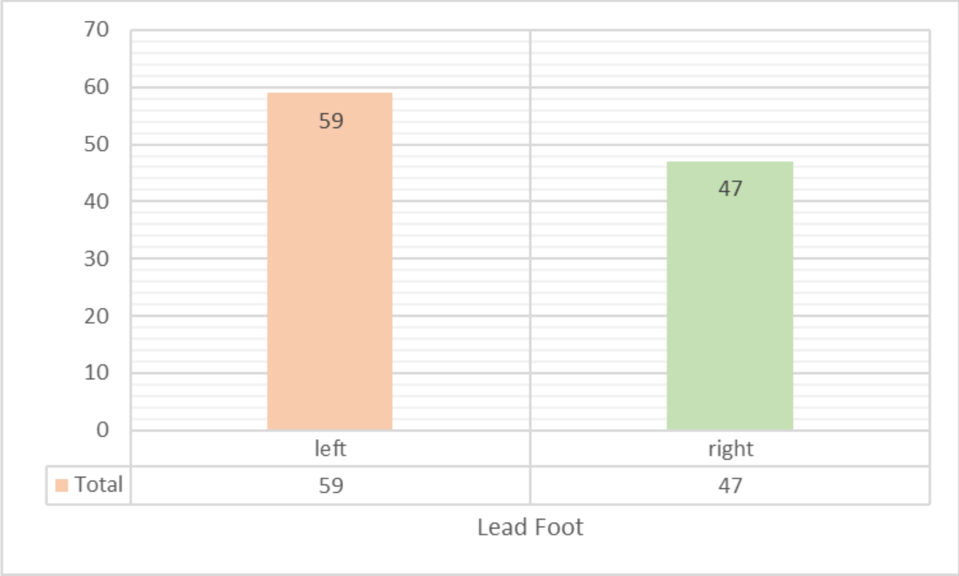

Figure 7: Distribution of Front Foot stance for athlete starts using the blocks

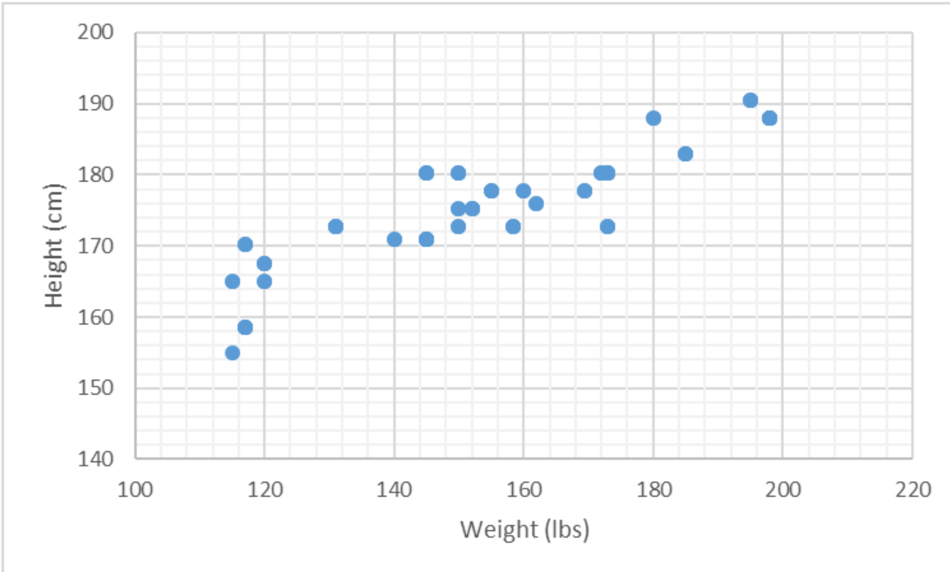

Figure 8: Distribution of Weight and Height of athletes tested

Table 7: Statistical Distribution of Athlete Height and Weight

	Mean	**Standard Deviation**
Height (cm)	174.4	9.41
Weight (lbs)	149.4	29.97

For the 106 sprint starts conducted, the mean and standard deviation of Athlete Age for the sample size of 106 is presented below, filtered by Athlete Sex.

Table 8: Distribution of Athlete Age by Sex

	Mean	**Standard Deviation**
Male	20.8	2.30
Female	18.6	2.53

Prior to the starts, the athletes were also given the blocks to inspect and set up as they would conventional starting blocks. Once set up, measurements such as incline angles from both blocks, length and width between the two blocks and athlete height, weight and age were then collected. Three practice starts were allotted to confirm that the set they had chosen was optimal and comfortable, before the Arduino was turned ON to collect the data. The coaches present allowed athletes to perform up to three consecutive, regular starts from the blocks, from which data was collected along with a video recording. After three consecutive starts the athletes were deemed tired by the coaches and retired to other training drills. The coach present reviewed the video footage and provided performance feedback in the form of a check list (see Appendix H) and a performance score out of 10.

As mentioned above, there were 103 trials performed which were scored by coaches. However, only 26 athletes were used. As such, some athletes contributed more starts to the data collected than others. At first glance, it would seem this imposes a bias in the data, as the dataset will favor some of the athletes more thoroughly than others. However, for this exercise the Coach Score is the variable that will be modelled rather than the data collected from the sensors. Therefore, due to repeated measure of the participating athletes and unbalanced observations in the number of starts or trials performed by the participating athletes, a Generalized Estimating Equation (GEE) was used to determine a Trial Effect Test [12]. Tables 9 and 10 show the number of athletes used for this project and how many starts or trials each athlete performed. It is clear that one of the athletes performed ten starts, while another athlete only performed one that was evaluated by a coach.

Table 9: Trial Effect Analysis Data Summary

Correlated Data Summary

Number of Levels	Subject Effect	**id**	26
Number of Subjects			26
Number of Measurements per Subject	Minimum		1
	Maximum		10
Correlation Matrix Dimension			10

Table 10: The number of athletes that completed a specific number of trial starts

Categorical Variable Information

			N	**Percent**
Factor	**trial**	1.0	26	25.2%
		2.0	24	23.3%
		3.0	17	16.5%
		4.0	11	10.7%
		5.0	8	7.8%
		6.0	6	5.8%
		7.0	5	4.9%
		8.0	3	2.9%
		9.0	2	1.9%
		10.0	1	1.0%
		Total	103	100.0%

Using the information from Table 10, a Trial Effect test can be performed in the IBM SPSS 23.0 Statistics software to check whether the trials impose a bias in this study i.e. whether the trials can be evaluated as independent trials.

Table 11: Trial Effect Test taking into account the number of athletes and start trials performed by each one

Tests of Model Effects

Source	Type III Wald Chi-Square	df	Sig.
(Intercept)	3825.478	1	0.000
trial	**51.216**	**9**	**.000**

Dependent Variable: score
Model: (Intercept), trial

Table 11 showcases the results of the test. These results indicate that for n trials, where n = 10, there is a statistically significant trial effect ($\chi^2(n-1) = 51.22$, $p < 0.001$) controlling for the participating athletes. In other words, the strong significance indicates that the trials are independent of each other, and that athletes who contributed multiple starts to the study did not impose a bias or imbalance in the evaluation of said data. This is further confirmed by the varying mean coach scores for each trial shown in Table 12.

Table 12: Mean and Standard Deviation in Coach Scores parsed by Trials

trial	Mean	Std. Error	95% Wald Confidence Interval Lower	95% Wald Confidence Interval Upper
1.0	**7.510**	.1690	7.178	7.841
2.0	**7.534**	.1913	7.159	7.909
3.0	**7.711**	.1906	7.337	8.084
4.0	**7.431**	.2266	6.987	7.875
5.0	**7.541**	.2368	7.077	8.005
6.0	**7.807**	.2220	7.372	8.242
7.0	**8.140**	.3392	7.475	8.805
8.0	**7.428**	.4113	6.622	8.234
9.0	**8.039**	.3530	7.347	8.731
10.0	**7.864**	.2384	7.397	8.331

5.2.1 Limitations

For this application, the Arduino is not capable of buffering data at a rate higher than 50Hz (20ms step size). A higher sampling rate would result in data loss and the Arduino misbehaving. A device capable of reading data at higher frequencies would be more expensive, which would go against one of the goals of this project of producing a marketable cost-effective, portable product.

Additionally, this apparatus is designed to measure changes in force, or pressure. The piezo-sensors only produce a voltage when they are subject to deformation, and a constant pressure does not produce a deformation on the sensor surface. As a result, it is very difficult to infer accurate net forces from the data collected. For instance, when the foot pushes against the blocks, it registers a spike in the data, which immediately decays to zero if the foot does not push harder. As such, rather than comparing the magnitude of the force data to that from literature, it is more worthwhile to compare the location and inherent pattern of the peaks on the time axis with that presented in literature [4]. This also enables us to statistically evaluate all of the data at face value, rather than performing a normalization to account for athlete weight and body type. The reason for this design decision was primarily minimizing production costs, and also keeping the design simple; so even if the sensor breaks, it can be replaced without much effort or affect the rest of the blocks in anyway. Further to this, the Arduino-sensor system does not directly measure forces. It measures the voltage change in the sensor in response to the forces, and converts this voltage measured at the pin of the Arduino board into an analog number between 0 and 1023. This is a limitation because accurate force measurements are not measured, rather inferred from a linearly proportional value. The linear relationship was confirmed during the impact test. The impact hammer, when released from increasing heights produced proportionally higher forces on the sensor, as measured by the voltage on the oscilloscope. The calibration for this force-to-voltage-to-numeric conversion was not performed due to the unavailability of the equipment, a MEMS device. However, since this apparatus measures a change in forces rather than net forces, this calibration step is not crucial to the scope of this research, but would be an important inclusion if this design is further pursued for commercialization.

Another limitation with this experiment is the availability of additional equipment and the actual athletes. Additional equipment such as timing-gates to gauge the impact of a sprint start on the acceleration phase of a sprint were only available for a handful of the starts performed, and as such the data is limited to draw formal conclusions about how sprint starts, or rather coach feedback about sprint starts affects the athletes' 30m race time.

Furthermore, the availability of an ideal distribution of athletes based on age, sex, height, weight, and experience is beyond the control of the researchers involved, and pursuing this distribution would require various excursions to other athletic clubs outside of Calgary; the funds for which were not available at the time of this research. It should also be mentioned that due to the limited number of athletes available, some athletes used these blocks more often than others, thus providing more sets of data. This imposed a bias on the data collected and the associated conclusions drawn due to some of the trials not being independent. However, as shown above, the statistical analysis presented in Tables 11 and 12 enable us to analyse their starts as independent and remove any statistical bias from the dataset.

The feedback noted by the coaches during this research may not align with other coaches who did not participate in this research. An effort was made to mitigate this by contacting the National Coaching Certification Program (NCCP) to formulate a standardized feedback form that would represent the views of various professional coaches on the criteria for visually judging a sprint start. The feedback form was not used during the data collection process to assign coach scores, but was used in the subsequent data analysis section. Even so, the limited number of coaches used in this study does impose a bias in resolving the telemetric data obtained from the blocks with the performance scores assigned by the coaches, and is thus definitely an aspect of the study subject to further refinement.

5.3 Data Evaluation

The data was imported in a Microsoft Excel 2013 spreadsheet to tabulate and graph. A sample graph from one of the elite athletes (Figure 9) illustrates the data collected from the starting blocks. The data was labelled by the time-stamp and subject ID number of when the video was taken on the camera. This allowed for very easy cross-referencing and correlation between the data and the video files. Since the Arduino Uno was only capable of 20ms sample time (50Hz sampling rate), the data was graphed as a discrete time function to emphasize the discrete time sampling.

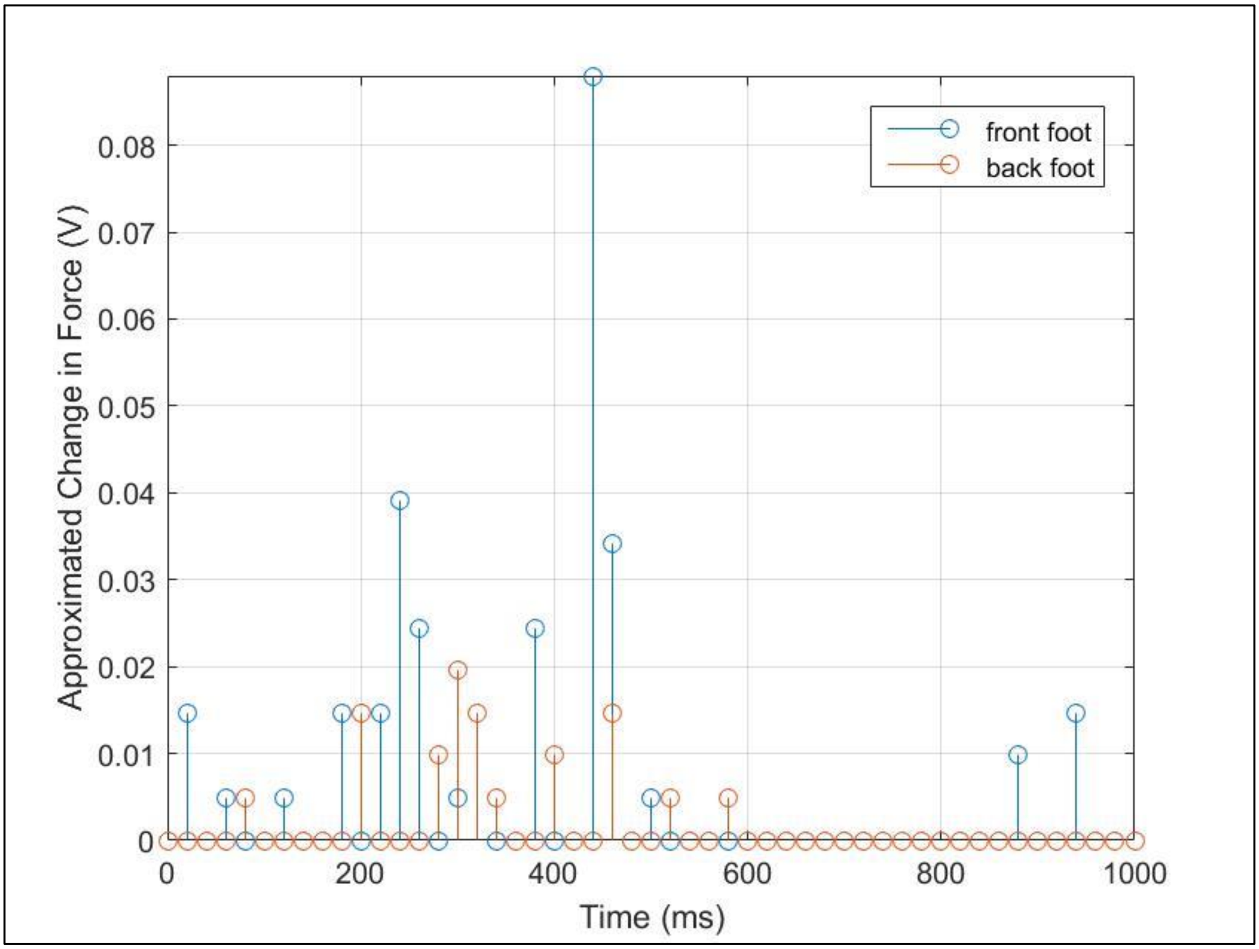

Figure 9: Sample Output from the data collected by the Arduino Uno and Piezo Sensors

The above graph, due to its discrete nature does not look like the data presented in literature [4]. As such, in order to illustrate the features and the important points from the graph that are used for further analysis, the above graph and all other graphs are plotted as continuous time figures (Figure 10). This does not affect the analysis in any way, and is done purely for presentation purposes.

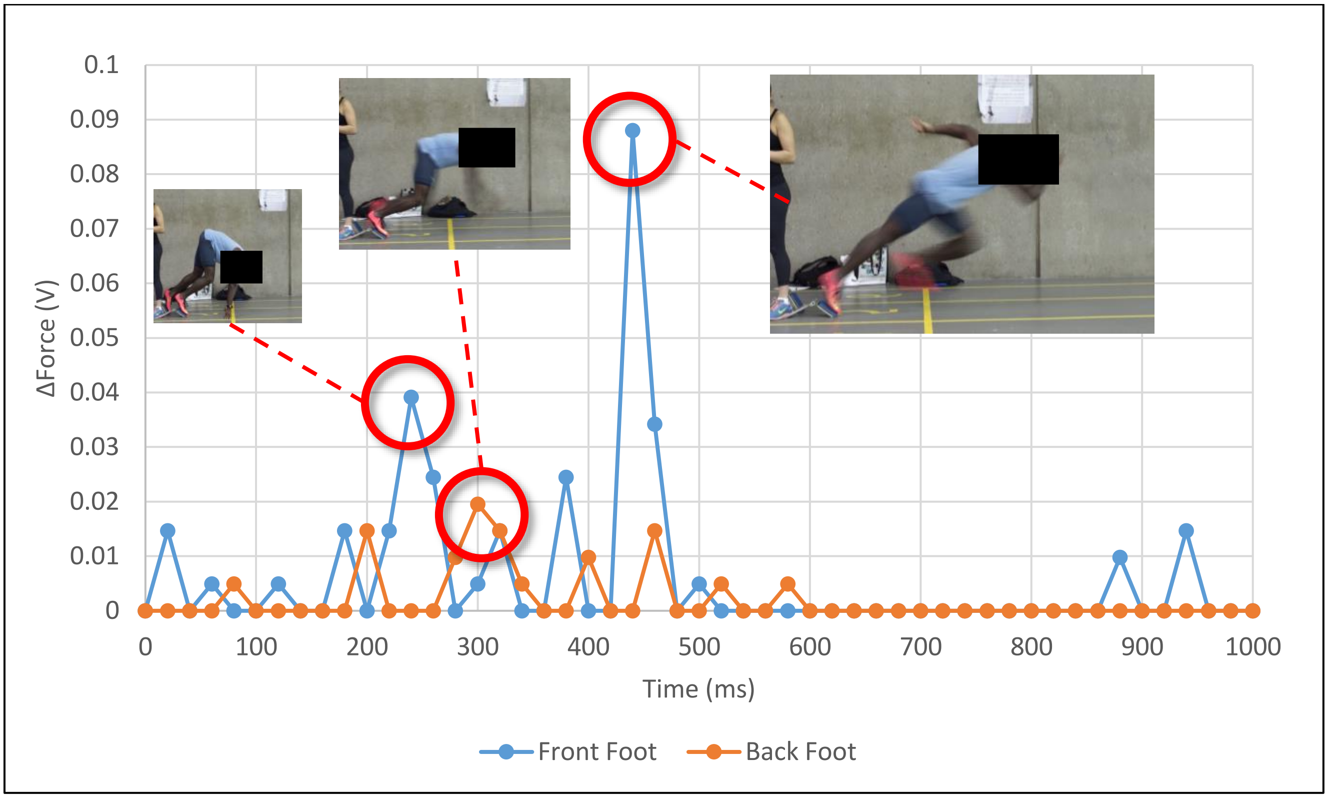

Figure 10: Elite Sprinter Starting Block Force vs Time Data (Reaction Time = 240ms)

There are two steep or outstanding peaks on the front foot, identified by the red circles, and one minor, yet still outstanding peak on the rear or back foot. At 0 ms on the graph, the starting gun is triggered. It is evident that right from this moment, the athlete's small flinches are recorded from the sensors in the blocks. It is not until 220ms that the athlete pushed off from the blocks – that is the first outstanding peak on the front foot. The outstanding peak on the rear foot is when that foot leaves the block and all of the athlete's weight momentarily is on his front foot (as evidenced by the second outstanding peak on the front foot). After which point the athlete has completely left the blocks. The two small peaks at approximately 900ms on the front foot are a result of the blocks moving due to the high impulse pushing force from the athlete, and are not collected from the athlete's feet but from residual vibration from the blocks being pushed back.

This is consistent with the findings reported in the Coh, et al. (1998) paper. In that paper, the authors measured the net force from each foot during a sprint start with a force plate. Since in this study, we are measuring instantaneous changes in force, we are essentially measuring a discrete time derivative of the net forces.

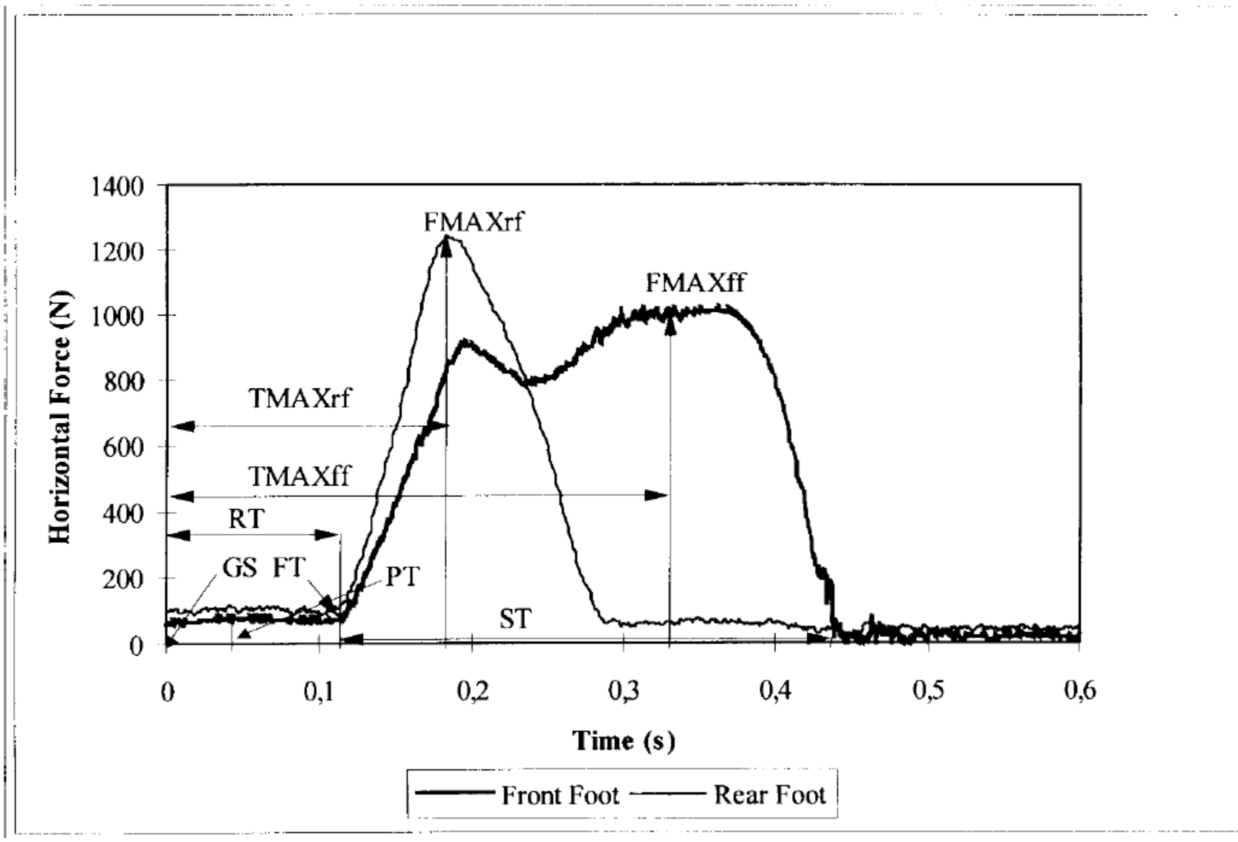

Figure 11: Horizontal Foot Force vs. Time [4]

Based on this knowledge, it can be seen that the two peaks measured on the front foot data in this study, correspond to the peaks on the front foot noted in the Coh, et al. (1998) paper. In Figure 11, the forces do not decay to zero because the system is measuring net or absolute forces, so as long as the feet are applying pressure to the force plates, some force will be measured. In the Coh, et al. (1998) paper, it can clearly be seen that the rear foot forces are higher than that of the front foot forces, and the rear foot force peaks at approximately the same time as the first peak of the front foot. This was only observed in our study with some of the athletes (Figure 12). For others, the rear foot peak was observed between the two front foot peaks, even among experienced sprinters. The change in forces measured was about the same or lower than that of the front foot force peaks. Now, since only the change in forces was being measured, the rear foot forces could very well be higher, but it cannot definitively be stated as such.

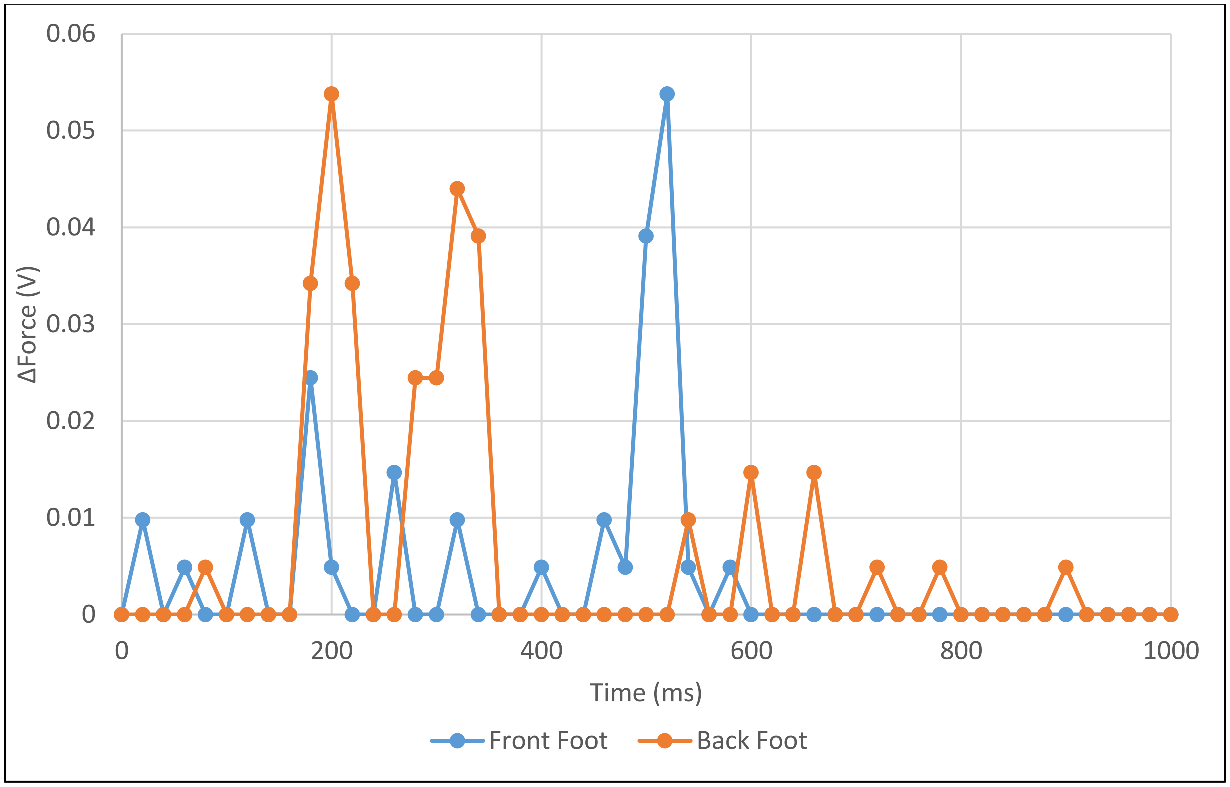

Figure 12: Data from another Male Sprinter's Start (Reaction Time = 180ms)

The magnitude and position on the time axis of these peaks was fed into the IBM SPSS Statistics 23.0 software for statistical correlation analysis with the coach feedback score.

A discrete time integration can be performed using the trapezoid rule on the data collected to further illustrate that the data collected in this study is consistent with the findings in literature [2] [4]. The integration will provide us with an estimation of the net force at each time interval, which when plotted should yield a shape similar to those presented in literature.

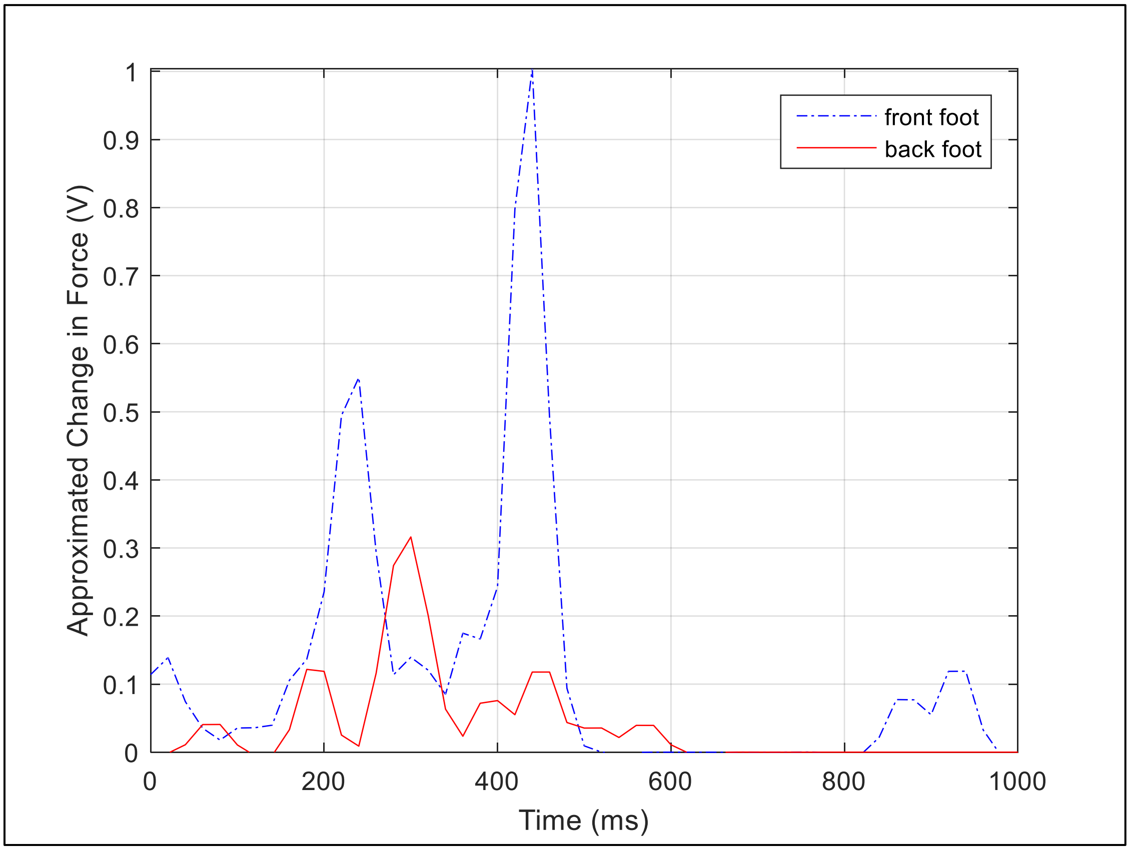

Figure 13: Discrete time integration on Force data from Figure 10

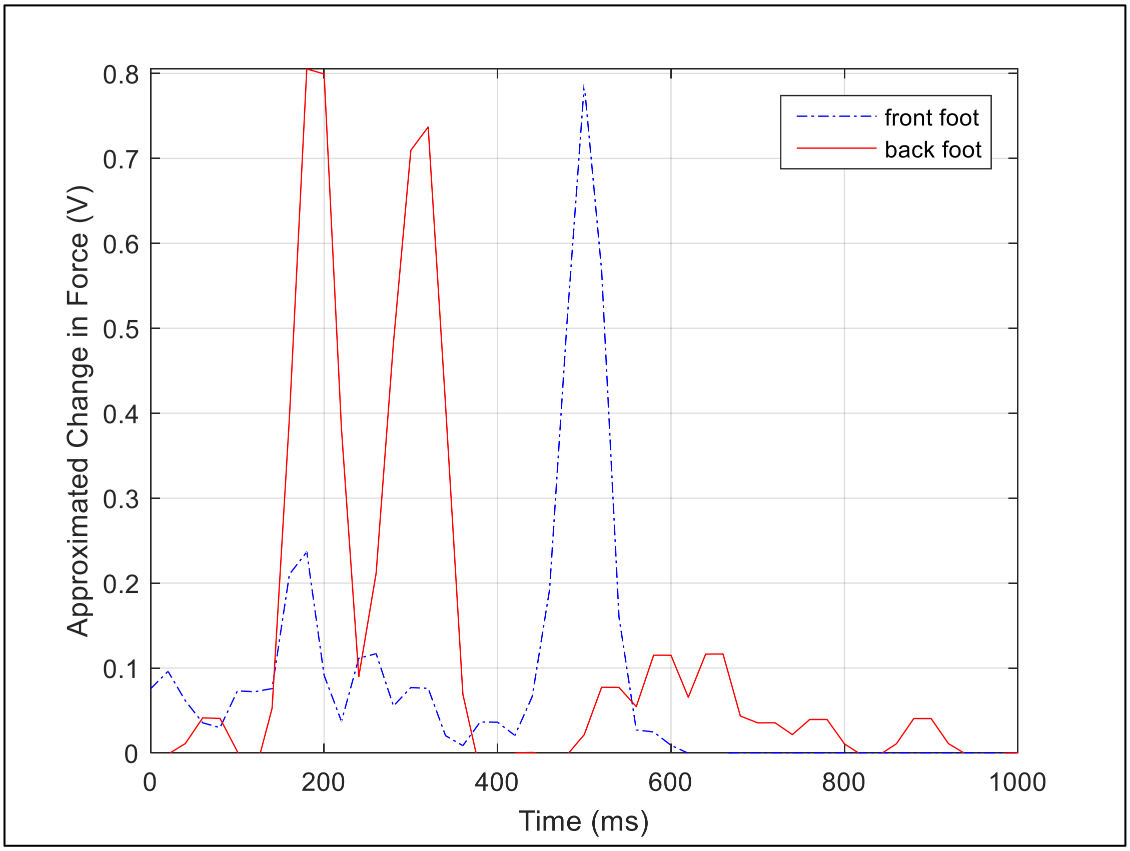

Figure 14: Discrete time integration from Force data in Figure 12

In the above figures, it can be seen that the trends are similar to the ones presented in Figure 11. The rear foot and the first peak of the front foot, both occur at the same time, and there is a definite sustained increase in forces on the front foot, around the 300ms to 400ms point. The exact time of the peaks depends on the athletes' reaction time, and as such, the time of the peaks in this study differ from the ones in literature, but the overarching pattern of the peaks remains consistent.

Chapter Six: Discussion

6.1 Introduction

It is evident from Chapter 5 that there are certain patterns emerging from the data collected; namely, the three-peak signature that every start seems to have. In this chapter, the patterns observed in Chapter 5 are discussed. A statistical analysis is performed for these patterns and the few samples that stray from the trend. The implications of these patterns are also proposed along with an example of an artificial intelligence fuzzy logic algorithm that can assign qualitative performance scores based purely on the quantitative dataset is also presented.

6.2 Discussion

The data collected was correlated with the Coach Score in SPSS Statistics software. A two-tailed Pearson correlation was performed between the peak forces from both feet, and the corresponding times at which these forces occurred for all starts. The most obvious parameter to correlate is impulse, since mathematically,

$$J = F * t$$

Where,

J = Impulse (Ns)

F = Force (N)

Δt = time (s)

The starting setup of the blocks was different for all sprinters, principally the incline angles of the blocks. The sensors measure change in force, or rather change in localized pressure, perpendicular to the plane in which they are located. Any other source of pressure or vibration is reduced by a component proportional to the difference in angle between the two planes, as is the case in kinematics. As such, the forces measured by the sensors, can be divided into individual components. Evaluating the components rather than the forces enables accommodating different incline angle setups for the blocks used by different athletes. After discussion with coaches, athletes, and the research listed in Chapter 2, Section 2.2, it was decided that the horizontal (thrust) component of the forces from the athletes' feet is the more important component and the performance feedback that coaches provide is primarily to maximize this quantity. Evaluating the individual components of the forces with the coach score would not only provide a good standardization of the forces, but will also be a more valuable correlation to coaches and athletes alike rather than just the net force.

Table 13: Pearson Correlation between the horizontal front foot peak force and Coach Score

Correlations

		Coach Score	$tl1*Fl1_x$
Coach Score	Pearson Correlation	1	.336**
	Sig. (2-tailed)		.002
	N	82	82
$tl1*Fl1_x$	Pearson Correlation	.336**	1
	Sig. (2-tailed)	.002	
	N	82	106

**. Correlation is significant at the 0.01 level (2-tailed).

Where,

tl1 = Time at which the first lead foot force peak occurs (ms)

$Fl1_x$ = Horizontal component of the lead foot force peak

A good correlation between two parameters would show a Pearson Correlation approaching 1 or -1. The closer the Pearson Correlation is to 1 or -1, the stronger the correlation.

Therefore, it can be stated that a Pearson Correlation of 0.336 is moderate. This is supported by the 2-tailed Significance of 0.002. A Significance value of < 0.05 is a very strong significance between two parameters i.e. increases and decreases in one parameter correlate strongly to increases and decreases in the other parameter. Given that the data was collected from human beings in a non-simulated environment such as a laboratory, and was correlated to qualitative scores from a coach, a moderate correlation still shows promise in terms of trending the data.

The one strange finding from this research is related to reaction time. The official standardized threshold for classifying a false start is 100ms. However, that is for the reaction i.e. the time at which a noticeable, visual flinch is shown by the athlete. It is not the time at which the athlete pushes off from the blocks. Due to the limitations of the Arduino Uno microcontroller, very accurate reaction times, on the order of milliseconds, was not possible to collect. As mentioned above, the smallest possible step size allowable by the Arduino for this program was 20ms, and as such the times measured from the blocks are at best an estimate.

On some of the starts, a noticeable visual flinch was noted by the coach however, the flinch was very insignificant when measured on the Arduino via the blocks. For example, on one of the starts, the athlete anticipated the "GO" command from the blocks signifying the starting gun, and visually flinched before the command actually occurred. The coach noted this as a false start and commented that this would be deemed a false start in competitive races as well. However, when reviewing the data (Figure 15 and Figure 16), the flinch noted only showed a change in force of 0.005V which is indistinguishable from the change on force recorded due to ambient vibrations on the track.

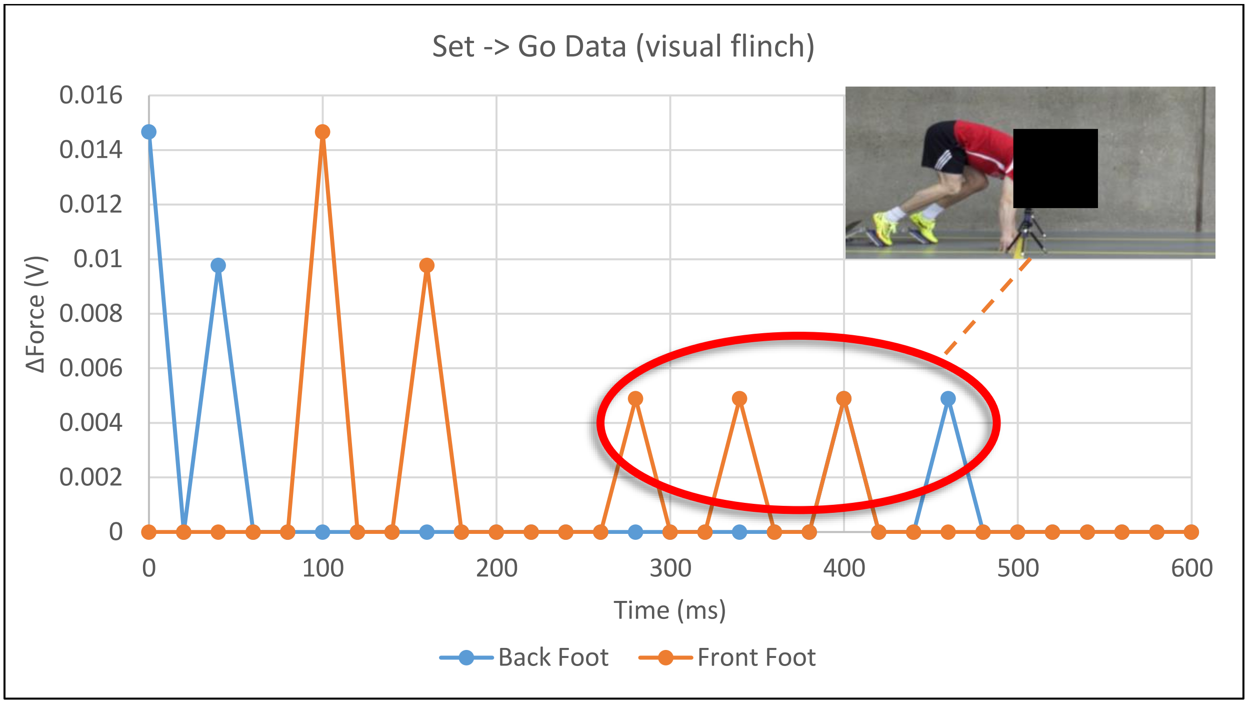

Figure 15: "Set" to "Go" Data where a visual flinch was observed by coach

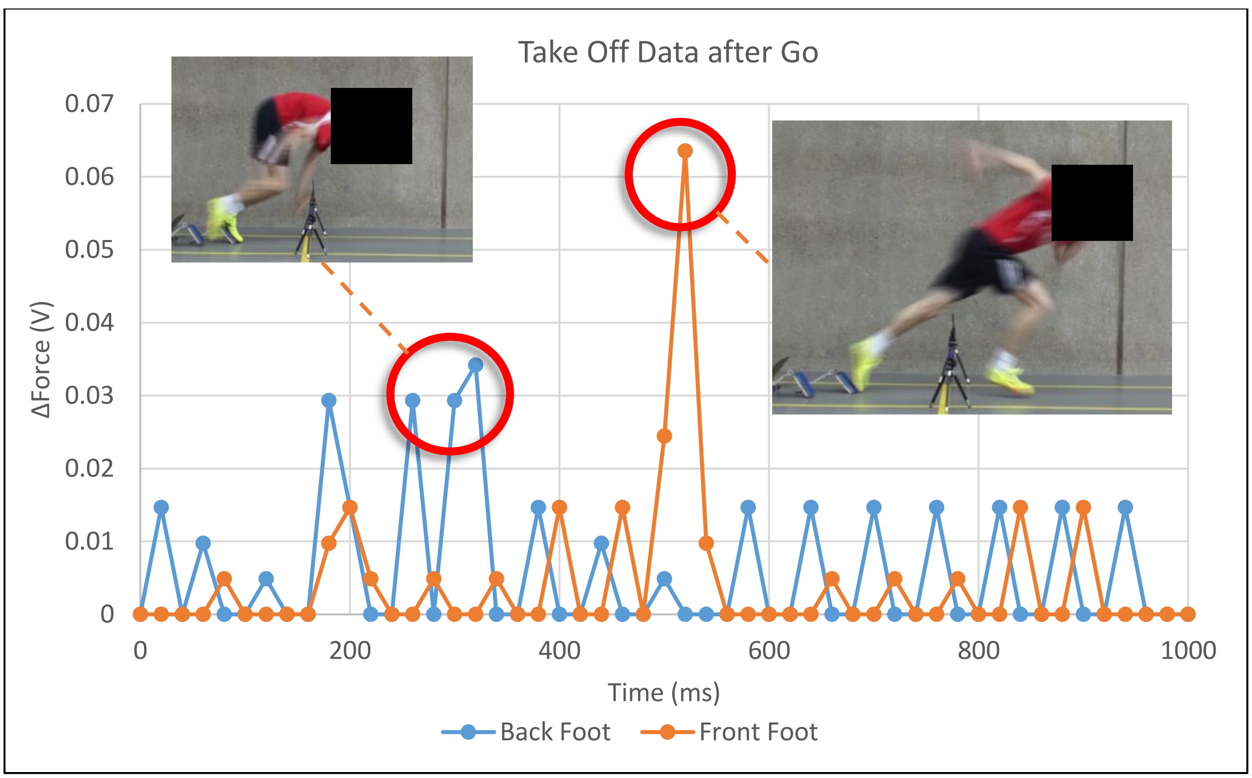

Figure 16:“Go” data after the visual flinch was noted by coach (Reaction Time = 180ms)

This is an interesting finding which demonstrates one of the limitations of these starting blocks as an outright substitute for coaches during solitary training schedules. It should be noted that the sensors did correctly identify a false start that was due to the athlete pushing on the blocks before the 100ms criteria [5].

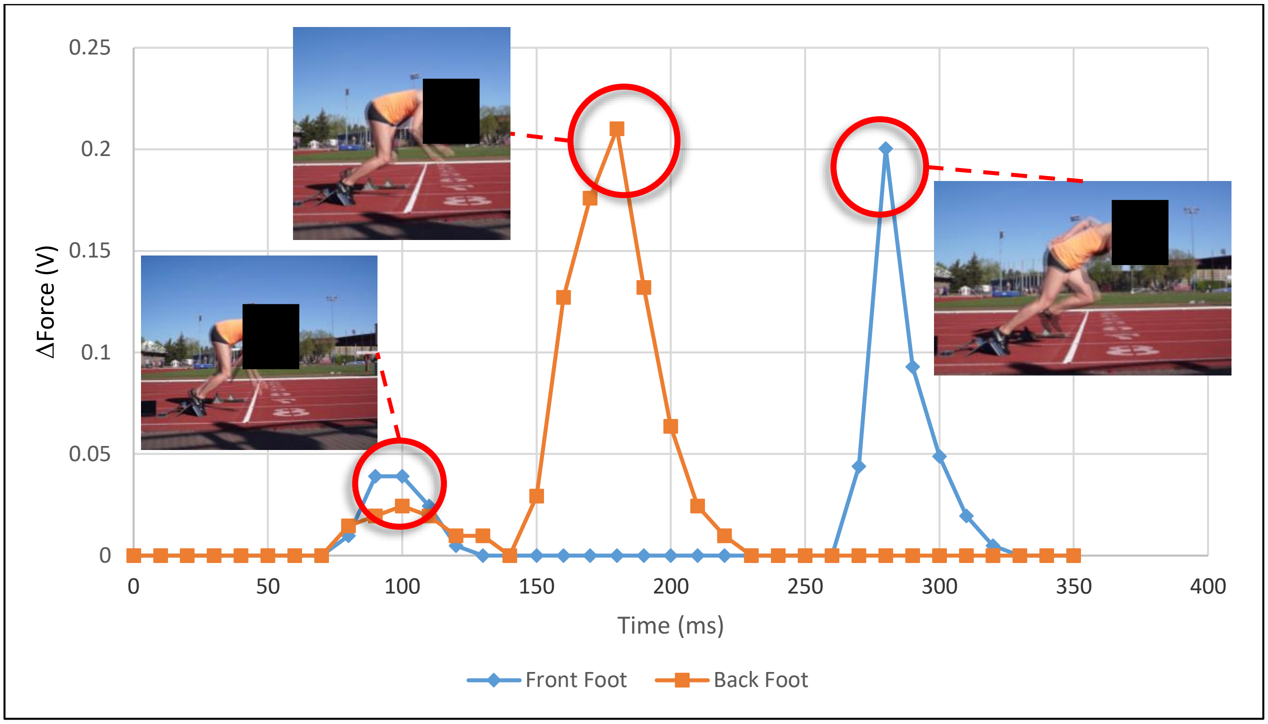

Figure 17: False Start correctly detected by the sensors (Reaction Time = 80ms)

The false start in Figure 17 was clearly a result of pushing before the 100ms criteria [5], and was correctly measured and identified by the sensor-microcontroller system. As such, these blocks are good at identifying false starts only if the false starts are a result of pushing before the 100ms criteria and not flinching.

Notably, almost every single sprinter who tried the blocks showed the same signature force peaks in their data. There are usually two peaks on the front foot, with one peak on the rear foot between the two front foot peaks. The first peak on the front foot is likely due to a weight transfer from the hips in order for the rear foot to take off. The peak on the rear foot plot is the rear foot pushing on the blocks to take off. The second peak on the front foot plot is the front foot pushing once the rear foot lands and the sprinter has taken his or her first step in the race. All other lesser peaks shown in the graph are due to small flinches from the athletes' feet and ambient vibrations. If an athlete is less experienced, or not "in season" which implies they are not competing imminently, they show more of these lesser peaks during the start (Figure 16), characteristic of hesitation, anticipation, and lack of focus. Whereas, a more experienced athlete who is more confident in his or her start will be calmer, more focused and have better posture in the blocks. As a result, fewer of the lesser peaks are observed during their starts (Figure 10 and Figure 17). This observation can be quantified mathematically and defined as start "Efficiency".

The efficiency is calculated based on which force peaks correspond to the sprinter actually pushing for a start, vs. any other minor force readings that can be attributed to flinches or noise that indicate the athlete is not confident or is trying to anticipate the start. The efficiency therefore can be defined as:

$$Efficiency = \frac{Area\ under\ Force\ Peak}{Area\ under\ the\ whole\ curve}$$

The "efficiency" was calculated based on the knowledge of which force peaks were actually made for pushing compared to the rest of the graph. Ideally, if there is only one peak per foot, that would imply that the sprinter was perfectly calm and used his or her effort only to push. If the graph is noisy, then it can be inferred that the sprinter was nervous or fidgety in the blocks thus affecting his or her concentration and thereby the start as well.

This value for efficiency was calculated for each foot independently. It was discovered (Table 14) that the maximum efficiency between the athletes' feet produced the best correlation with the Coach Performance Scores, rather than correlating each foot's efficiency with the Coach Score independently. This correlation, although poorer than the one observed in Table 13 between the Horizontal Front Foot Peak Force and the Coach score, is a better parameter to model a sprint start performance scoring algorithm. This is because the Efficiency parameter takes into account all the data collected once the "Go!" takes place; rather than just one data point in the case of the Horizontal Front Foot Force.

Table 14: Correlation of Efficiency and Coach Score

Correlations

		Coach Score	Max efficiency
Coach Score	Pearson Correlation	1	.201*
	Sig. (2-tailed)		.042
	N	103	103
Max efficiency	Pearson Correlation	.201*	1
	Sig. (2-tailed)	.042	
	N	103	106

*. Correlation is significant at the 0.05 level (2-tailed).

Based on the efficiency correlations, a fuzzy logic algorithm can also be designed to compute an estimated sprint start score that can be relied upon during the absence of a coach.

6.2.1 Fuzzy Logic Algorithm

A fuzzy logic algorithm was also devised to provide estimated performances scores for the sprint starts in the absence of a coach. Fuzzy Logic was the best candidate to use for this algorithm because it was heuristic in nature and rule-based. As mentioned in Chapter 2, Section 2.3, in order to categorize data into various segments, in this case, performance scores, a rule-based system is easiest to work with and is the most adaptable. The other knowledge-based systems are not as applicable for this study since they need to be trained or optimized before being useful. The training also makes these algorithms very unreliable since the performance scores they calculated would be biased to the dataset used to train the algorithm. The fuzzy logic algorithm is composed of three parts:

- Peak-finding
- Calculate start efficiency
- Assign Fuzzy Score

As mentioned above, the front foot and rear foot show distinct peaks and a pattern that is consistent with the different start data collected. As such, if these peaks can be found and classified, the front foot and rear foot can be distinguished automatically within the algorithm, without having to manually assign them.

The second part is the calculation of the start efficiency. The efficiency can be calculated based on the definition above and used to design the fuzzy logic rules. Five rules were devised each associated with a performance score range:

- 1.0-2.9
- 3.0-4.9
- 5.0-6.9
- 7.0-8.9
- 9.0-10.0
- 0.0 is defined as a false start.

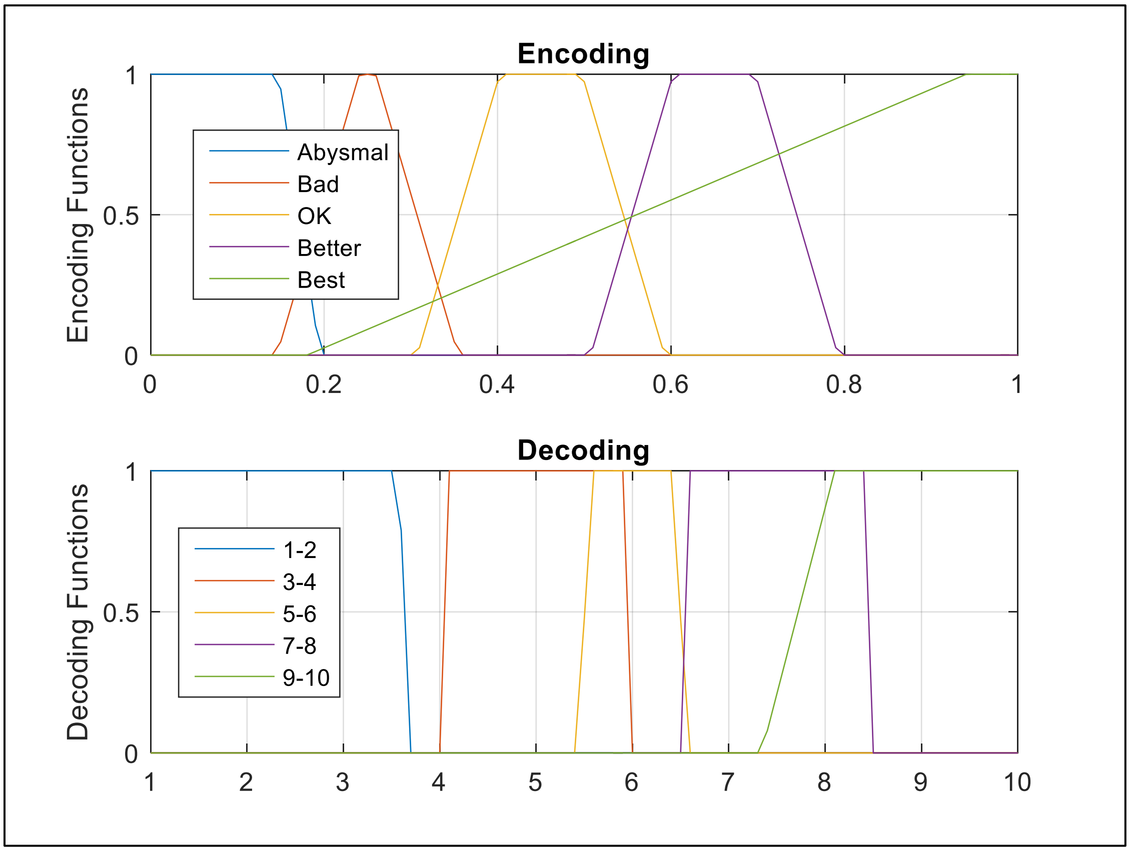

Figure 18: Fuzzy Sets for calculating Performance Score

Five rules were formulated because the coaches only gave scores in 0.5 increments on a scale of one to ten. Formulating ten rules (one for each incremental score) or more is redundant and provides the same results as conditional statements. Formulating fewer rules reduces the variance in the fuzzy output which is not very informative to athletes and coaches. In other words, with fewer rules an algorithm will only show a change in the performance score for drastic changes in the sprint start dataset rather than for minor variations.

The fuzzy logic was designed as a Centre of Gravity(COG) method for simplification in the defuzzification process. The overall schematic of the algorithm can be shown below.

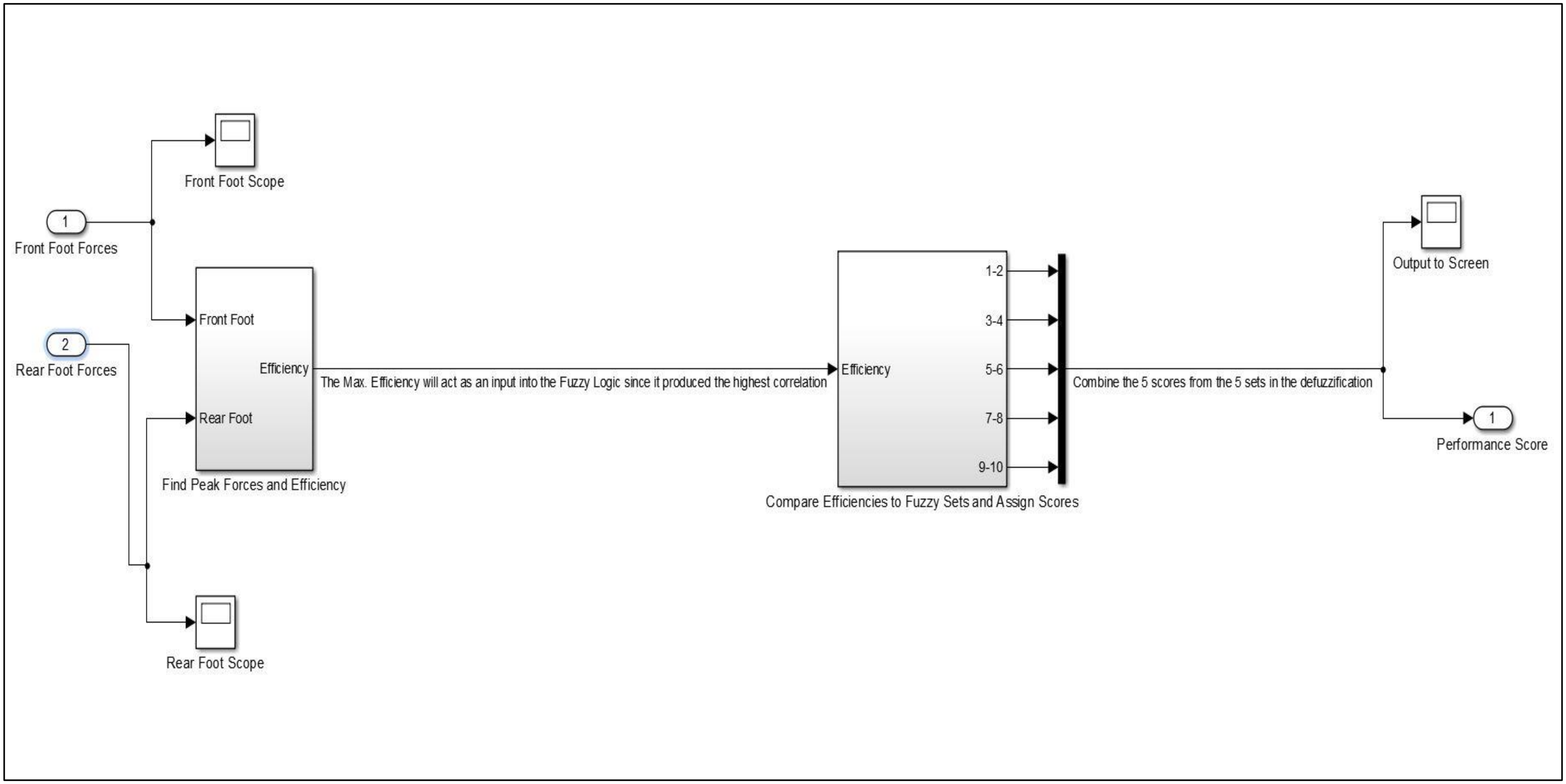

Figure 19: Fuzzy Logic Algorithm Schematic

The performance scores obtained from this fuzzy algorithm can thus be compared and correlated to the scores obtained from coaches.

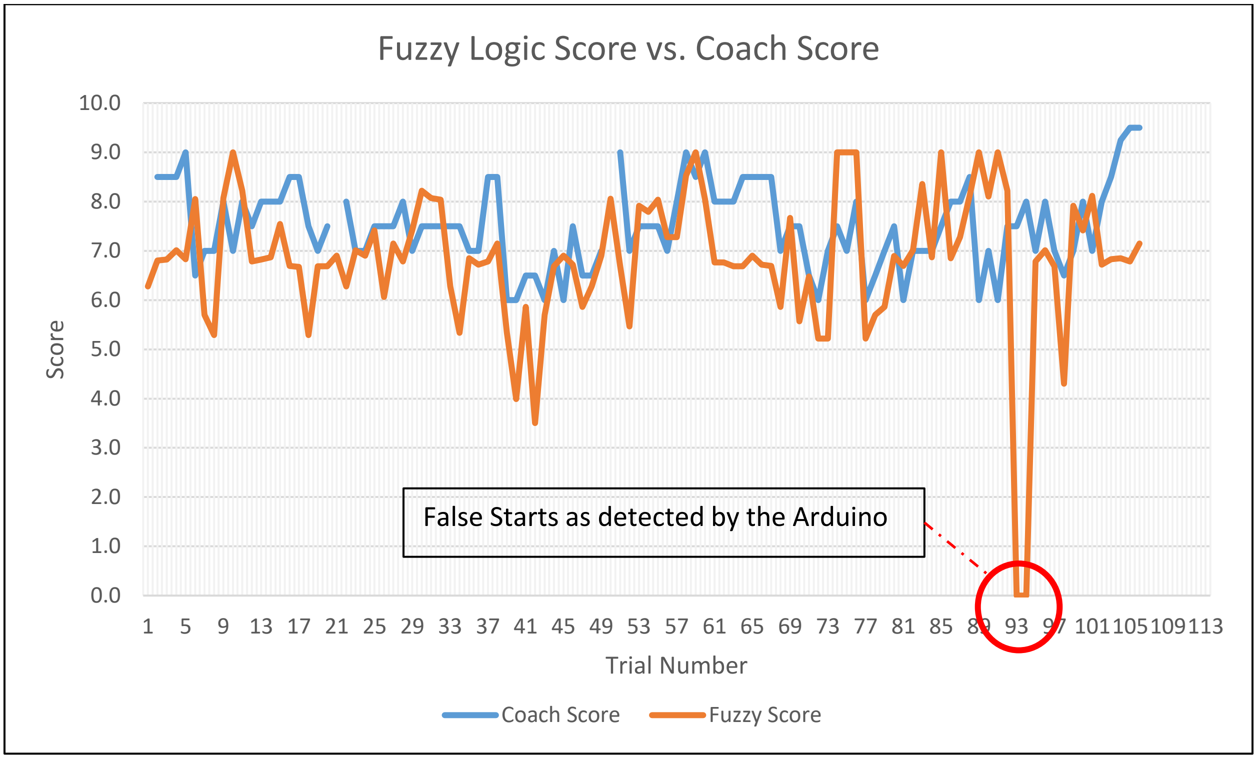

Figure 20: Fuzzy Logic Algorithm Score vs. Coach Score

It can be seen from Figure 20 that fuzzy logic scores are generally more conservative than the coach scores but still very closely related. The conservativeness of the fuzzy scores can be attributed to the fact that these scores were based on the forces exerted on the blocks during a start rather than the qualitative eye of a coach. As such, if the athlete didn't push hard enough, even though they may have had a good start according to a coach, the start will be graded more strictly by the fuzzy logic algorithm.

Table 15: Coach Score vs. Fuzzy Logic Score Correlation

Correlations

		Coach Score	Scores from Fuzzy Logic
Coach Score	Pearson Correlation	1	.312**
	Sig. (2-tailed)		.001
	N	103	103
Scores from Fuzzy Logic	Pearson Correlation	.312**	1
	Sig. (2-tailed)	.001	
	N	103	106

**. Correlation is significant at the 0.01 level (2-tailed).

Chapter Seven: Conclusions

7.1 Introduction

In this chapter, the patterns observed in Chapter 6 are discussed and conclusions based on these patterns are formulated. The implications of these conclusions and how they impact the contributions proposed in Chapter 3 are also discussed.

No study is without its shortfalls and as such, a list of the shortfalls of this study is also presented in this chapter. A summary of associated future studies that can build upon this thesis is also presented, followed by a short summary of the conclusions of this study.

7.2 Contributions and Conclusions

In this final section, I can highlight how various conclusions obtained from this study accomplish the various contributions listed in Chapter 3.3 and reiterated below:

1. A redesign of the Capstone project portable sprint starting blocks that is lighter due to the thinner steel used in its construction along with a bespoke Arduino microcontroller shield that enables the input from two piezo sensors embedding in the blocks.
2. An updated version of the starting gun command program in the Arduino Microcontroller that features more realistic delays between the starting gun commands, namely, “Ready”, “Set”, and “Go!”.
3. Detailed impact hammer testing and associated results with multiple sensors that was performed in order to select two sensors that output the same voltage for a given input force.
4. Extensive multi-subject study with athletes and coaches that looks into the optimization of sprint starts.

5. Statistical correlation of the qualitative coach performance feedback score and the quantitative data collected from the blocks.
6. Design of a fuzzy filter/algorithm that interprets the data collected from the starting blocks' sensor system and suggests a performance score.

The blocks, as designed during the Capstone Project, were portable, light-weight, self-contained, and intuitive to use [1]. They were further lightened for this thesis by using thinner steel when compared to the original Capstone proto-type. The prototype model used for testing was quite popular among the athletes who tried them, and the coaches too. The design methodology and justification can both be found in Chapter 4, under the Starting Block Design section.

The program written to simulate sprint starting commands had to be made such that sprinters cannot anticipate the starting gun, and yet realistic enough that sprinters are not stationary in the blocks for too little or too much time between commands. As such, a duration between the "Set" and "Go" commands that was randomly selected between pre-set limits helped eliminate this issue. The program also included a method to check if a false start was performed in the event the user of the blocks flinched or left the blocks before or within 100ms of the starting gun command being issued. This conformed with the prevailing IAAF rules and regulations as well [5].

The sensor validation as described in Chapter 4 was also performed with an impact hammer for this project. The findings from this test showed that the orientation of the soldered leads on the sensor affect the voltages generated by the sensor when struck with an impulse force. The test also confirmed that the piezo sensors are not calibrated by the manufacturer, as some produce higher voltages for the exact same amount of force than others.

The sensors implemented in the blocks offer a cost-efficient means of collecting valuable telemetric data during a sprint start, and crucially, are non-intrusive. This means that any athlete can use the blocks without having to wear a harness or device of some sort which might impede their movement and affect their performance. The sensors also are very sensitive and when properly secured, highly durable as well.

The coaches definitely took to the idea of a portable, intelligent starting block system that can provide quantitative validation to their qualitative feedback. Their appreciation for the blocks and this study even prompted them to help me produce a standardized rubric or checklist that would be universally applicable to coaches who grade sprint starts. The checklist was produced with co-operation from the National Coaching Certification Program (NCCP), and is attached in Appendix H.

Finally, the force and time data that was collected during the sprint start unfortunately did not correlate well enough with the associated coach feedback score to define a mathematical model so that the blocks could predict the performance score in the absence of coaches. However, the statistical correlation showed that during a sprint start each of the sprinter's feet shows distinct, predictable behaviors which was used to develop an intelligent control algorithm to predict the performance scores.

The calculated scores from this intelligent fuzzy logic algorithm were more conservative than the actual coach performance scores since they were reliant solely on the forces collected, rather than other qualitative data like sprinter posture, arm-drive, and so on which a coach would also factor in. Even so, it definitely shows that modeling a sprint start purely on telemetric data collected is possible and if refined with better technology, could aid sprinters in many ways to improve their performance using real data.

The one shortcoming of this design was the inability to accurately measure all the cases of false starts, as was evidenced when one of the athletes visibly flinched before the starting gun but the forces were barely registered on the blocks. As such, the blocks can be used to measure reaction times and calculate false starts if the false start was a result of an actual push, but cannot be used to validate flinches as false starts.

It should also be noted that the statistical correlations stated in this report are moderate, rather than strong. This can be attributed to many factors such as the variation in sprinters used, the skill level of the athletes, the biases of the coach, or even the limitations of the Arduino itself as a data collection module. As such, these correlations are subject to further refinement with more advanced equipment, and a larger sample size of athletes and coaches. The correlation performed as part of this study are moderate, yet show a strong significance, which alludes to the theory that there is something to be found from additional research on this specific part of the study.

The study on the whole can be characterized as a success since it showed that the idea of a portable set of sprint starting blocks which can collect data from sprinters and aid coaches in providing performance feedback is indeed possible. Further to this, the data collected from the starting blocks showed some interesting trends that provide more insight into the biomechanics of a sprint start. The design is a testament to what can be accomplished with simple materials, rudimentary engineering prowess, and the application of feedback received from a target demographic.

7.3 Future Work

In this section, I outline a list of projects that can be undertaken to expand upon the deliverables of this study. In order to improve the results in this study, one can recruit more athletes of more varying diversity in age, sex, height, weight and experience to further validate the results obtained in this study. One can also conduct this study in other locations around the globe to see if the environment has an effect on the results. This would not only provide more data and more coaches for this expert system type problem, but will also make the data more variable which in turn would enable us to statistically generalize the findings based on the sample size to the global population.

Having stated this, we can delve into a list of studies can be made to expand on the results of this one. Firstly, with access to a more expansive machine shop and more funding the starting blocks themselves can be manufactured to be more durable and lighter. This can be done by manufacturing a custom ratchet mechanism out of lighter materials than steel such as magnesium or aluminum thus enabling the remainder of the blocks to be also made from a lighter material. One can also resort to a different type of connection than welding between the plates and the ratchet hinge; this, although sacrificing durability, might enhance the portability even more by making the blocks modular. Efforts can also be made in improving the Arduino interface to produce a better marketable product. Improvements such as enabling a connection between the Arduino and the LCD screen shield or going a step further to implement communication between the Arduino and a modern smartphone to eliminate the need for a computer for data collection and analysis will further enhance the portable nature of the product. Some of the athletes commented that calibrating the sensors to display forces in Newtons, and implementing a sensor to measure absolute forces will provide valuable information towards quantifying their sprint start performance.

To expand upon the academic contributions of this study, one can improve the fuzzy logic algorithm for judging performance scores by implementing a training algorithm such as neural networks to adapt fuzzy logic to each individual athlete. This would enable the controller to provide personalized scores based on the sprinter's performance thus perhaps accelerating their growth in the sport even more. The only downside with this is that this upgrade will eliminate any possibility of the blocks being used competitively since the scores won't be comparable to one another since each athlete is unique. However, data obtained from this personalized algorithm can be used to set more realistic thresholds for false start detection that vary from athlete to athlete. It has already been discussed that the current rule for false start of a 100ms reaction time is unrealistic. Hence, this upgrade might provide some insight in the area of false start detection and perhaps provide a precedent for the sport.

Lastly, the sensor system used in this project can be used in conjunction with force plates and video capture equipment in a controlled laboratory environment. This will not only calibrate the sensors with the forces measured by the force plate, but will also provide useful information in painting a more complete picture about the biomechanics of a sprint start.

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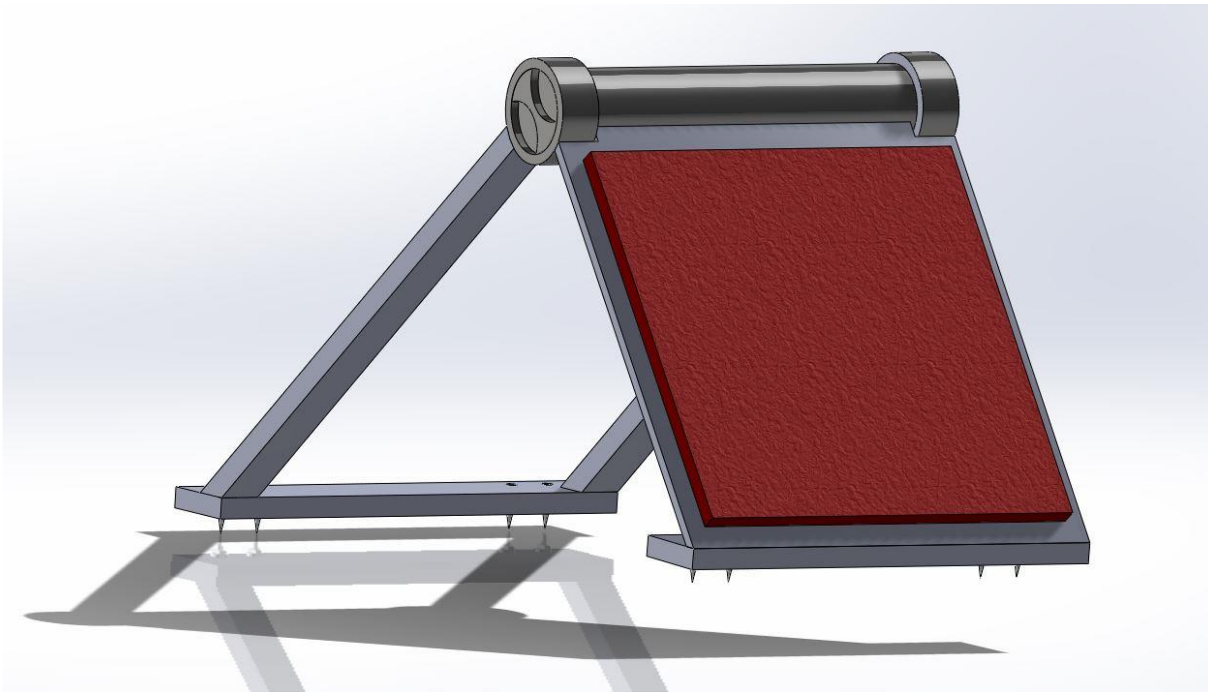
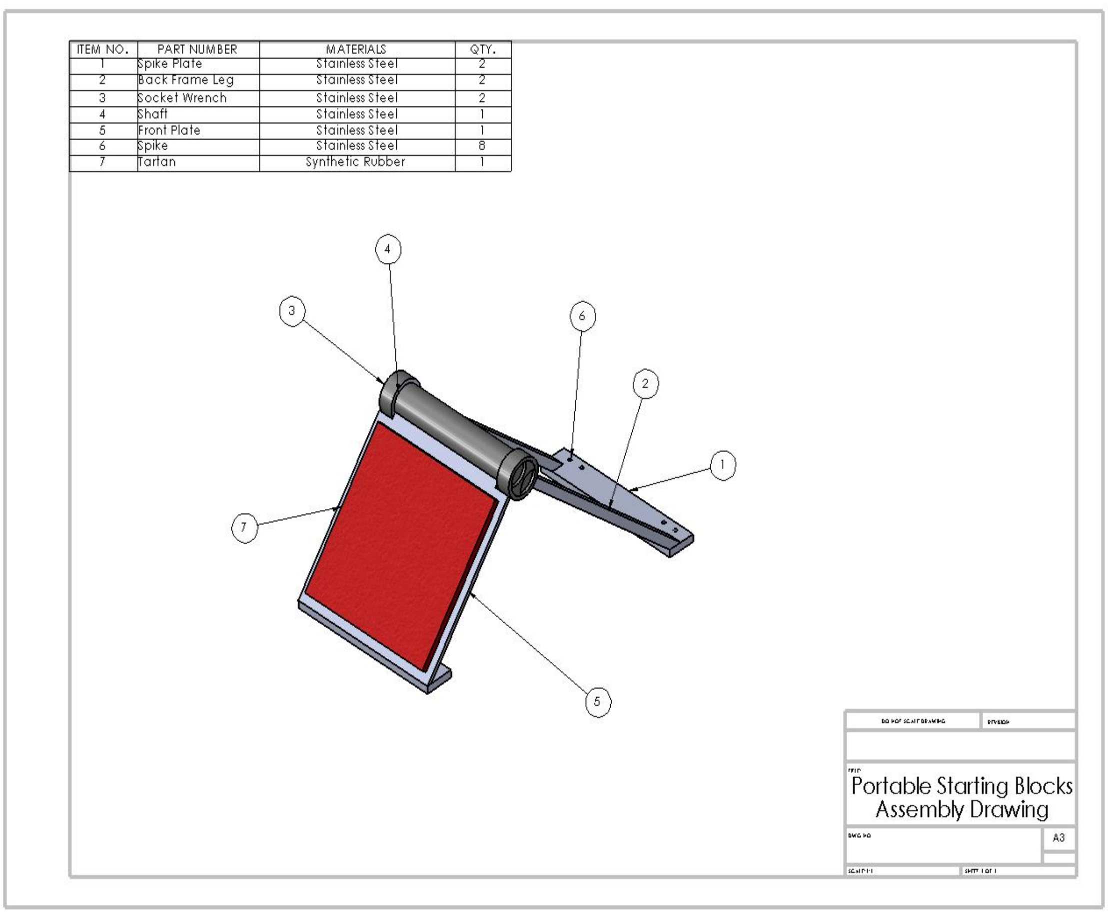
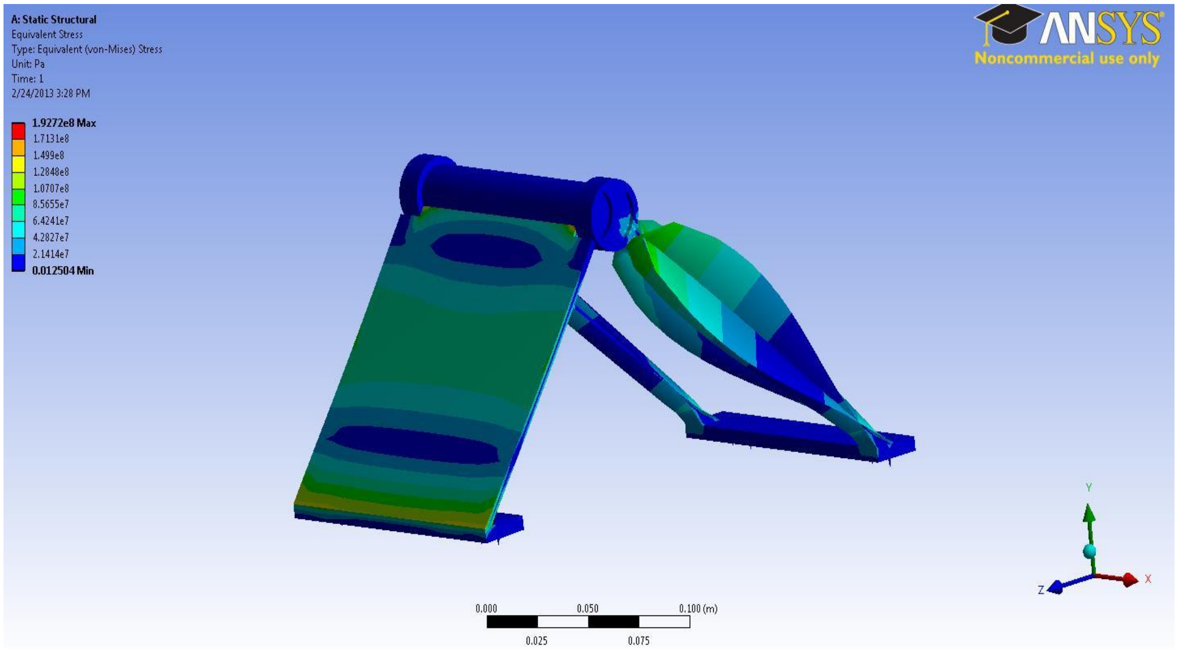
Appendix A: MISCELLANEOUS PHOTOS OF SPRINT STARTING BLOCKS DESIGN

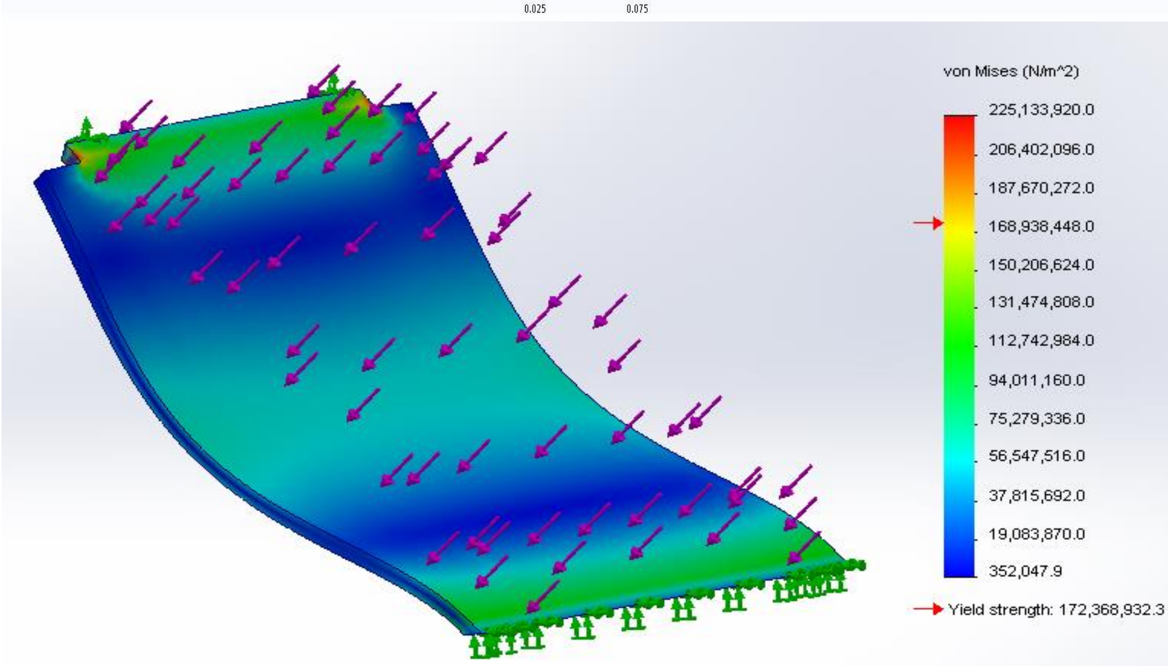
This appendix includes all the photos of the sprint starting blocks collected during the manufacturing and testing phases of this project right from its inception during the Capstone phase [1]. The photos will offer more detail on the design of the blocks to readers than the description in this thesis.

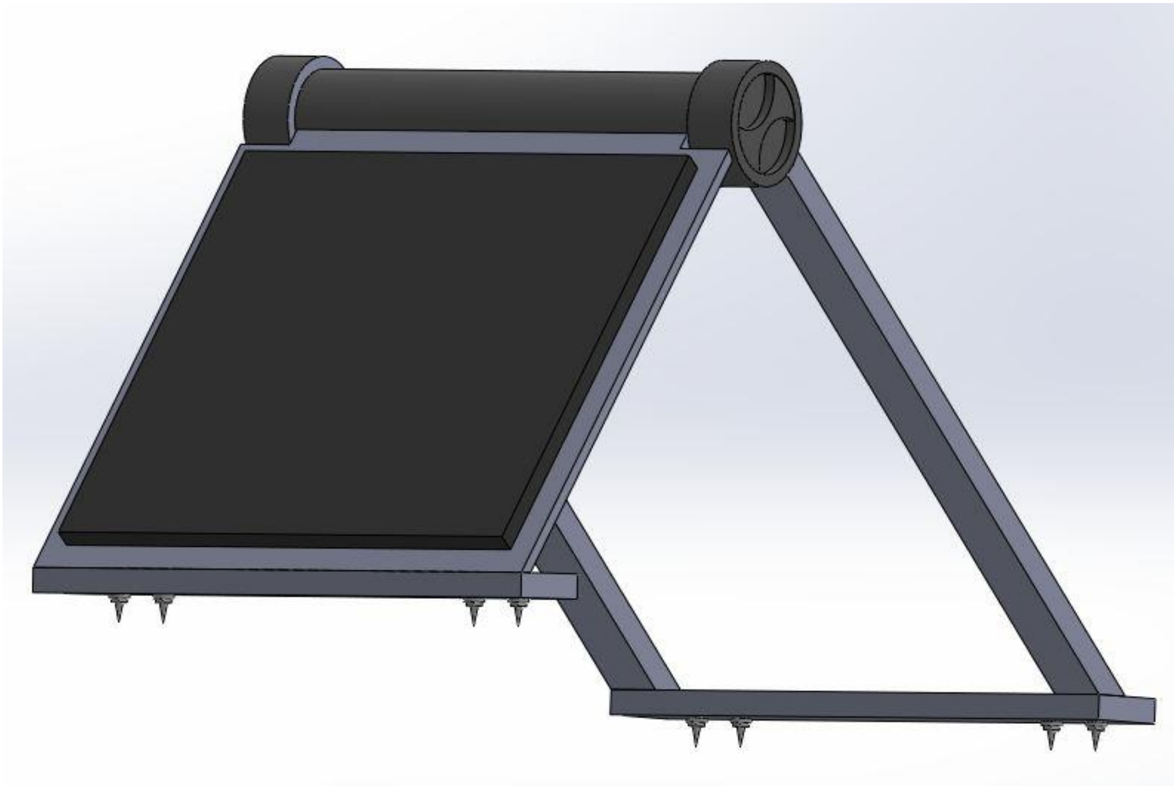


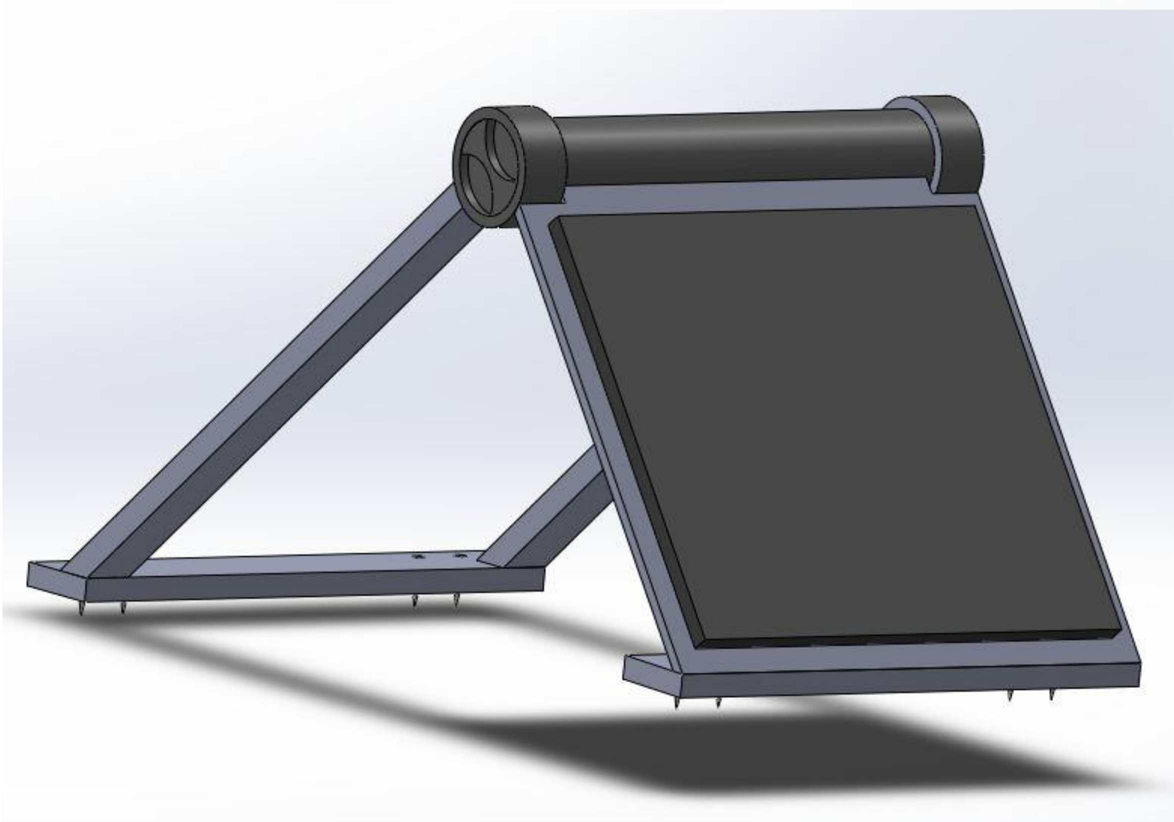


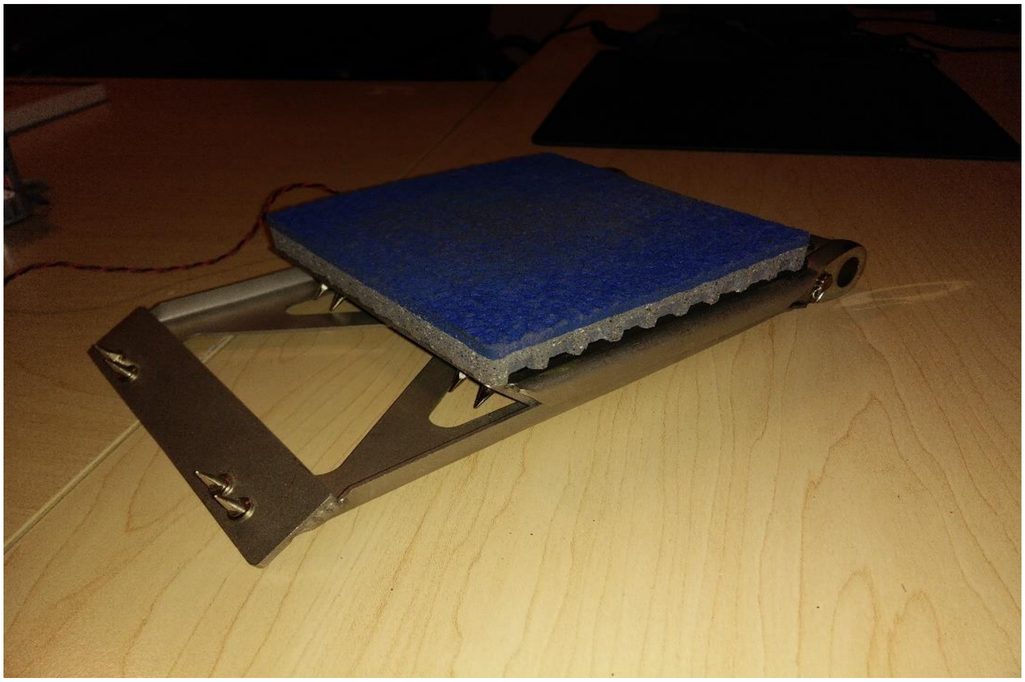
ITEM NO. | PART NUMBER | MATERIALS | QTY.
1 | Spike Plate | Stainless Steel | 2
2 | Back Frame Leg | Stainless Steel | 2
3 | Socket Wrench | Stainless Steel | 2
4 | Shaft | Stainless Steel | 1
5 | Front Plate | Stainless Steel | 1
6 | Spike | Stainless Steel | 8
7 | Tartan | Synthetic Rubber | 1
4
3
6
2
1
7
5
Portable Starting Blocks
Assembly Drawing
A3

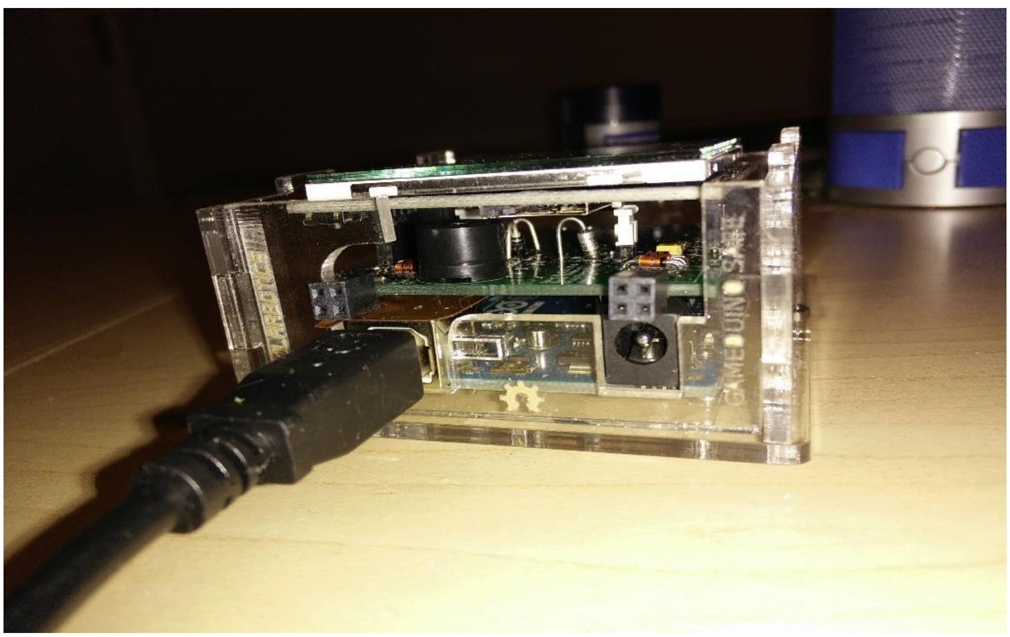

A: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: Pa
Time: 1
2/24/2013 3:28 PM
1.9272e8 Max
1.7131e8
1.499e8
1.2848e8
1.0707e8
8.5655e7
6.4241e7
4.2827e7
2.1414e7
0.012504 Min
ANSYS
Noncommercial use only
0.000
0.050
0.100 (m)
0.025
0.075
Y
Z
X

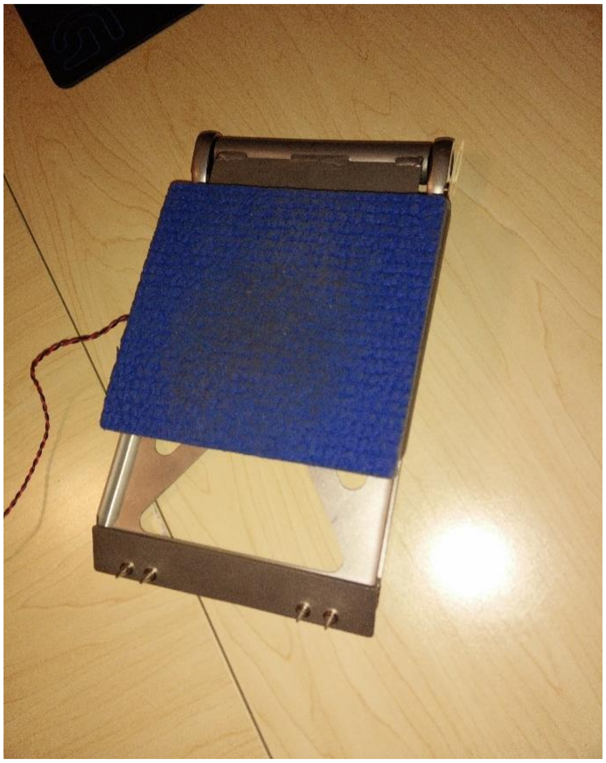

von Mises (N/m^2)
225,133,920.0
206,402,096.0
187,670,272.0
168,938,448.0
150,206,624.0
131,474,808.0
112,742,984.0
94,011,160.0
75,279,336.0
56,547,516.0
37,815,692.0
19,083,870.0
352,047.9
Yield strength: 172,368,932.3





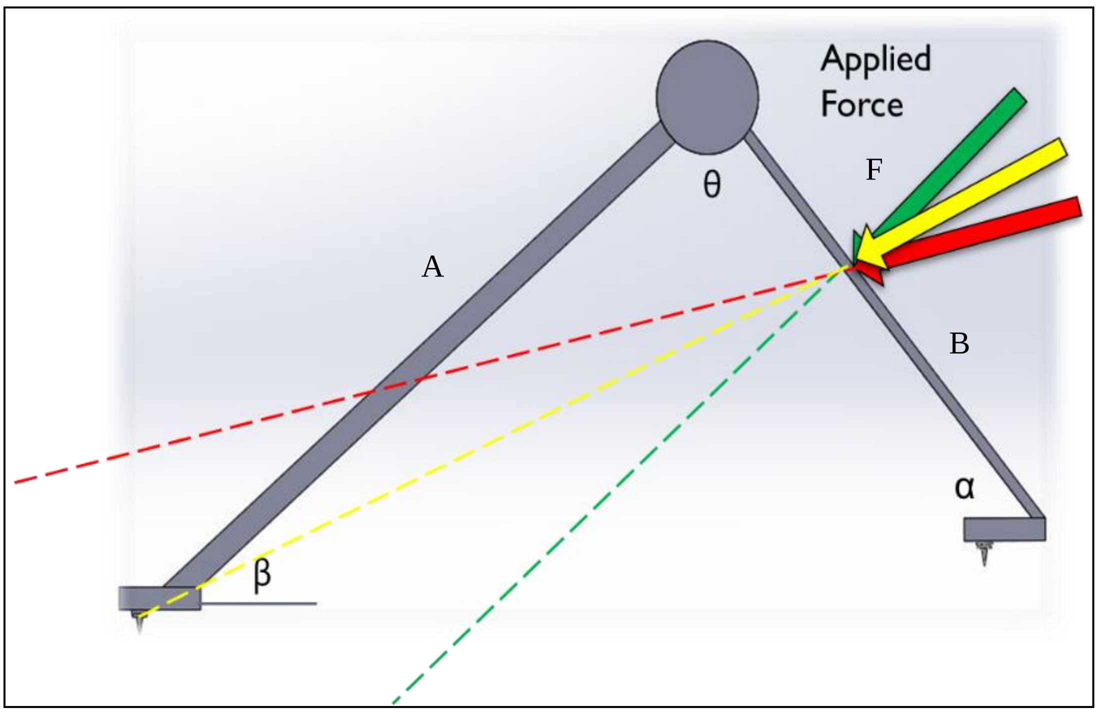



GAMEDUINO




Appendix B: CALCULATIONS TO VALIDATE THE DIMENSIONS OF THE STARTING BLOCKS AND THE HINGE

This appendix details the calculations performed to determine the dimensions of the blocks, specifically the length of the back plate to counteract any positive moment induced on the blocks during the start. Calculations to validate the strength of the ratchet as a hinge for the blocks are also included in this appendix. The calculations for the hinge were performed in an excel sheet with parameters such as steel grade and young's modulus as inputs. Here it must be noted that the symbols correspond to the sides and angles made by modelling the starting block as a geometric object in two dimensional space. As such, the definitions are as follows:



Symbol	Inputs			Theta	Theta_Rad	Alpha	Alpha_rad	L1	X	L2	Fx
A	0.3	m		40	0.698132	68	1.178372	0.208701	0.038434	0.09286	1528.926
B	0.15	m		45	0.785398	74	1.285872	0.221044	0.028249	0.096448	1666.823
HF	0.67			50	0.872665	79	1.386515	0.233772	0.018416	0.098798	1817.586
Mass	85	kg		55	0.959931	85	1.481216	0.246735	0.008991	0.100097	1980.508
WF	1			60	1.047198	90	1.570796	0.259808	6.16E-18	0.1005	2155.628
g	9.81			65	1.134464	85	1.485622	0.272882	0.00855	0.100136	2201.145
				70	1.22173	80	1.404235	0.285864	0.016662	0.099109	2264.916
				75	1.308997	76	1.32611	0.298674	0.024346	0.097506	2345.982
				80	1.396263	72	1.250799	0.311242	0.031614	0.095398	2444.156
				85	1.48353	67	1.17792	0.323506	0.038476	0.092843	2559.932
				90	1.570796	63	1.107149	0.33541	0.044945	0.08989	2694.456
				95	1.658063	59	1.038208	0.346906	0.05103	0.08658	2849.564
				100	1.745329	56	0.970862	0.35795	0.056741	0.08295	3027.888
				105	1.832596	52	0.904906	0.368502	0.062085	0.07903	3233.03
				110	1.919862	48	0.840163	0.378526	0.067068	0.074848	3469.843
				115	2.007129	44	0.77648	0.387989	0.071695	0.070428	3744.861
				120	2.094395	41	0.713724	0.396863	0.075971	0.065793	4066.951
				125	2.181662	37	0.651777	0.40512	0.079898	0.060963	4448.345
				130	2.268928	34	0.590534	0.412736	0.08348	0.055959	4906.285
				135	2.356194	30	0.529903	0.41969	0.086717	0.050798	5465.79
				140	2.443461	27	0.469799	0.425962	0.089612	0.045497	6164.484
				145	2.530727	23	0.410148	0.431536	0.092165	0.040074	7061.588
				150	2.617994	20	0.350879	0.436397	0.094377	0.034544	8255.896
				155	2.70526	17	0.29193	0.440531	0.096248	0.028924	9925.33
				160	2.792527	13	0.233241	0.443928	0.097779	0.023229	12425.84

```
L1 = sqrt(a^2 + b^2 - (2*a*b.*cosd(theta)));
L2 = (HF).*(a*b./L1).*sind(theta);
x = (1/a./sind(theta)).*L2.* L1 .* cosd(asind(a.*sind(theta)./L1));
Fx1 = Fy .* (L1 - x) ./ L2;
F1 = (1/a) * Fx1 .* L1 ./ sind(theta);
```

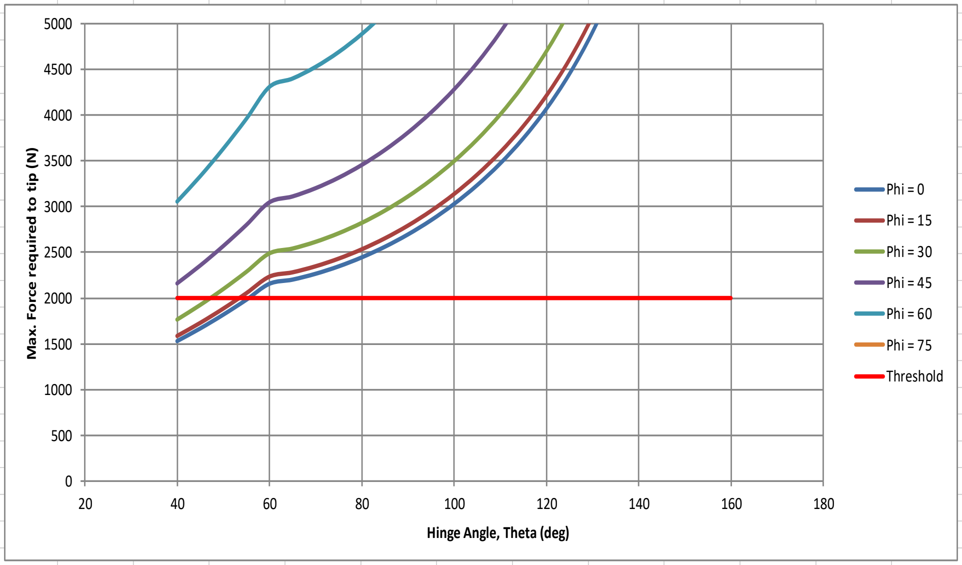
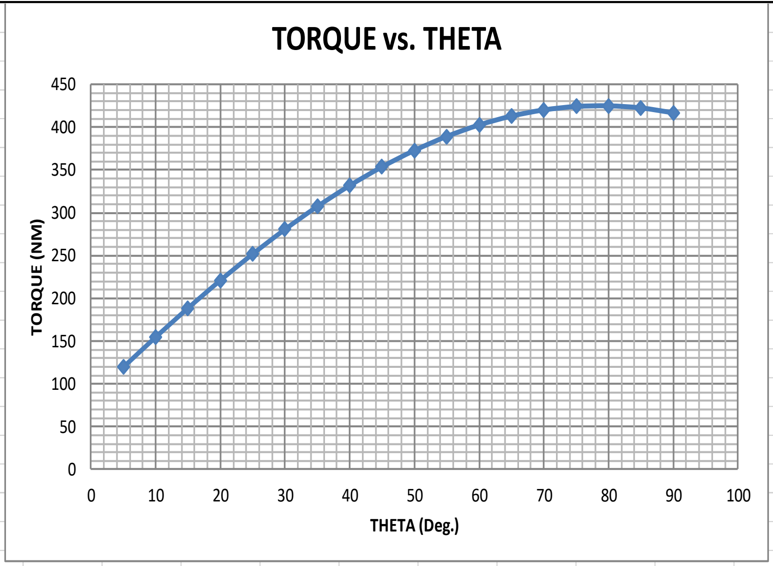


Plate:	0.15	m		Theta	Torque (Nm)
m:	85	kg		5	119.3870496
Fy:	833.85	N		10	154.4814121
Fx:	4169.25	N		15	188.4012688
Distance away from the hinge:	0.1	m		20	220.8887306
				25	251.6967987
				30	280.5912427
				35	307.3523812
				40	331.7767521
				45	353.6786595
				50	372.8915854
				55	389.2694561
				60	402.6877522
				65	413.0444561
				70	420.2608266
				75	424.2819986
				80	425.0773994
				85	422.6409818
				90	416.9912695



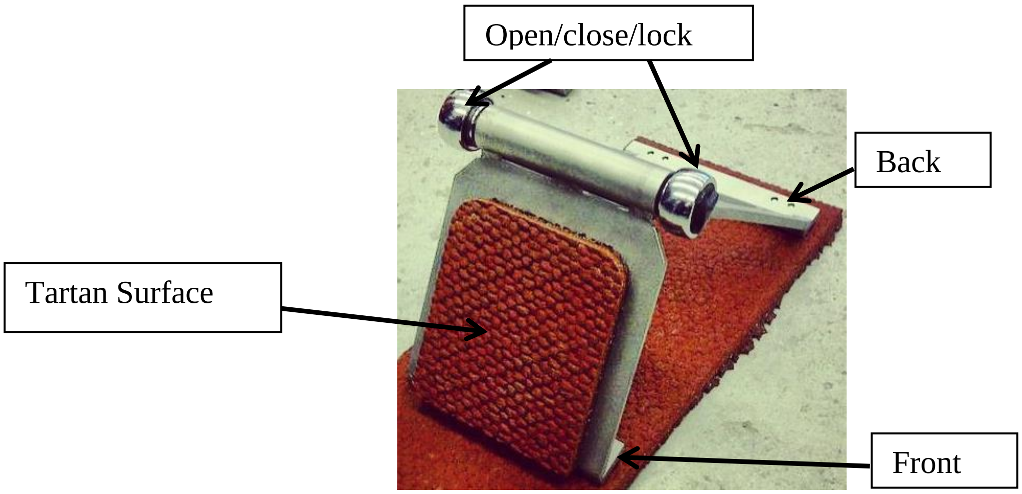
Size	Reasonable Maximum Limit*
3/4″ Square	2,035 Nm
1″ Square	4,750 Nm
1-1/2″ Square	15,600 Nm
2-1/2″ Square	61,015 Nm
3-1/2″ Square	135,590 Nm
4-1/2″ Square	271,165 Nm

http://www.imperial-newton.com/socket+select.htm

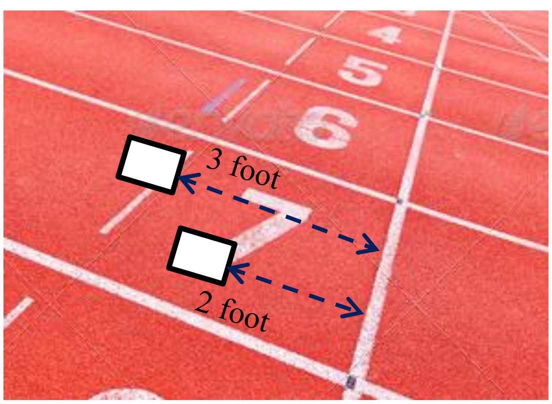
Appendix C: USER MANUAL FOR STARTING BLOCK PROTOTYPE

In this appendix, I detail a user manual created for the blocks during the Capstone Design Phase of the project to illustrate the documentation needed to convert this design into a marketable product [1]. The user manual is designed for athletes being introduced to the product for the first time and to guide them through the hinge mechanism and how to set the blocks up. It is assumed that once athletes have used the blocks, they become comfortable with the design, and also their preferred setup for the start.

Jet Setters Starting Blocks User Manual



Block Placement:

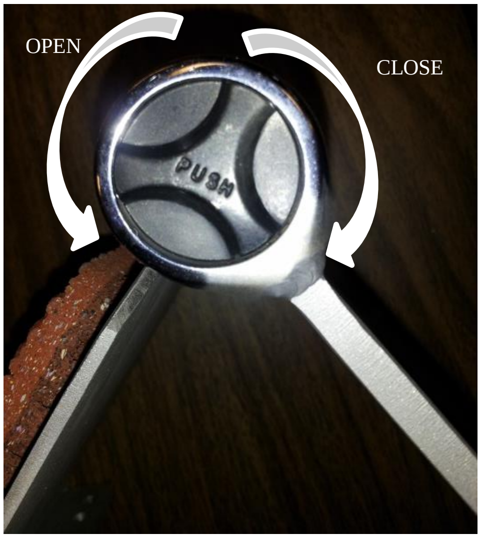


The position of where to place the blocks is very much up to personal preference. If you are familiar with sprint blocks, place them where they feel most comfortable. If you are new to using starting blocks, below is a general guideline.

1. Starting behind the start line, measure 2 foot lengths. Place the first block at this distance.
   - This should be the block for your stronger foot.
   - When placing blocks, ensure the tartan surface is facing forward and the front of the blocks are parallel to the starting line.
   - When sitting in your blocks, your front knee should just touch the start line.

2. Measure 3 foot lengths from the start line and place the second block.
   - The width between the blocks should be roughly shoulder width apart (measured from the middle of the blocks.)

Opening and Closing Starting Blocks:



To Open: Turn both switches on the blocks towards the front plate. Lift the front plate to the desired incline.*

To Lock: Once the desired incline is chosen, turn one switch to the CLOSED position. (It does not matter which side is set to OPEN and which side is set to CLOSED as long as the two switches are in the opposite directions.)

To Close: Turn the switch that is currently in the OPEN position to the CLOSED position and move the front plate back towards the back plate when finished.*

Cautions: It is not recommended to use inclines greater than 75 degrees. As a guideline, if the front spikes are not in contact with the track surface, the incline angle is too high.

<u>Storing blocks:</u>
Turn both switches to the close position and collapse the blocks so that the front and back plates are now in contact.

Incline Angles:

Graduated marks can be found on the right incline/ locking switch. Inclines can be adjusted every 5 degrees. The following numbers correspond to the following angles (angles are measured from the ground to the inside of the front plate):

1 - 75 degrees

2 - 60 degrees

3 - 45 degrees

4 - 30 degrees

Sensor:

The sensor has the ability to measure several different aspects of a sprint start: the sprinter's reaction time, which in turn can detect a false start, and the force generated throughout the start. For the best reaction time, ensure that the block that includes the sensor is the rear foot block.

According to the International Association of Athletics Federations, a false start is when a sprinter either 1) leaves the blocks prior to the starting gun or 2) reacts to the starting gun in less than one-tenth of a second (100 milliseconds).

The sensor used in the blocks is a piezo-disc sensor. The sensor is placed underneath the center of the tartan surface. For the best results, the sprinter should place their foot directly above the sensor.

To use the sensor, simply plug the block with the sensor into the plug located on the controller. A micro-USB to USB cord is also required to plug into a computer. The sensor outputs through the electronics into an Arduino Uno micro-controller; therefore, Arduino© software on a laptop is needed when utilizing the false start application.

<u>Procedure</u>:

1. Go to the Arduino© website, and download the free Arduino-1.0.4 software for your operating system. (http://arduino.cc/en/main/software)
2. Follow the online procedure to install the necessary driver software from the website. (http://arduino.cc/en/Guide/ArduinoDue)
3. Open the unzipped Arduino-1.0.4 folder and start the program.
4. Open the Jet_Setters code in a new window. To run the program, click the “Upload” button.

5. Once the upload has finished, click the “Serial Monitor” button.

6. The "Serial Monitor" will display the entire code and the results of the sprint.

7. To repeat, simply click the “Upload” button, followed by the “Serial Monitor” button and the program will reset.

<u>Using the Program</u>:

After clicking the “Serial Monitor”, a series of beeps will sound:

1. The first beep informs that the program has begun and that the sprinter can now get into the blocks.
2. After 10 seconds, another beep will sound, informing the sprinter to be "Ready".

3. After 6 seconds, the "Set" command will beep. The sprinter should now be ready to take off at any instant.
4. The "Go" command is the next beep; if can be differentiated because it lasts longer than other beeps. This command has been randomized from 1 -3 seconds from when the “Set” beep sounds. This prevents sprinters from trying to anticipate the starting command.
5. If a false start has occurred, a double gunshot will sound.

Interpreting the Results:

All recorded data can be analyzed through the Serial Monitor:

1. The reaction will be output at the bottom of the program. This is the reaction time when the sprinter reacts to the "Go" sound. If the sprinter leaves the blocks prior to the "Go" or prior to 100 milliseconds after the "Go", they incurred a false start. The program will output a double gun sound and the serial monitor will display the false start on the screen.
2. The maximum force applied can be determined by scrolling through the data set; the peak force recorded will be the instant the sprinter leaves the block.

The sensor's primary function is to help sprinters optimize their starts. For first time users, optimal block placement and incline settings can be determined by sensor results. A sign of improvement is when quicker reaction times (without incurring a false start) and higher peak voltages are recorded.

References:

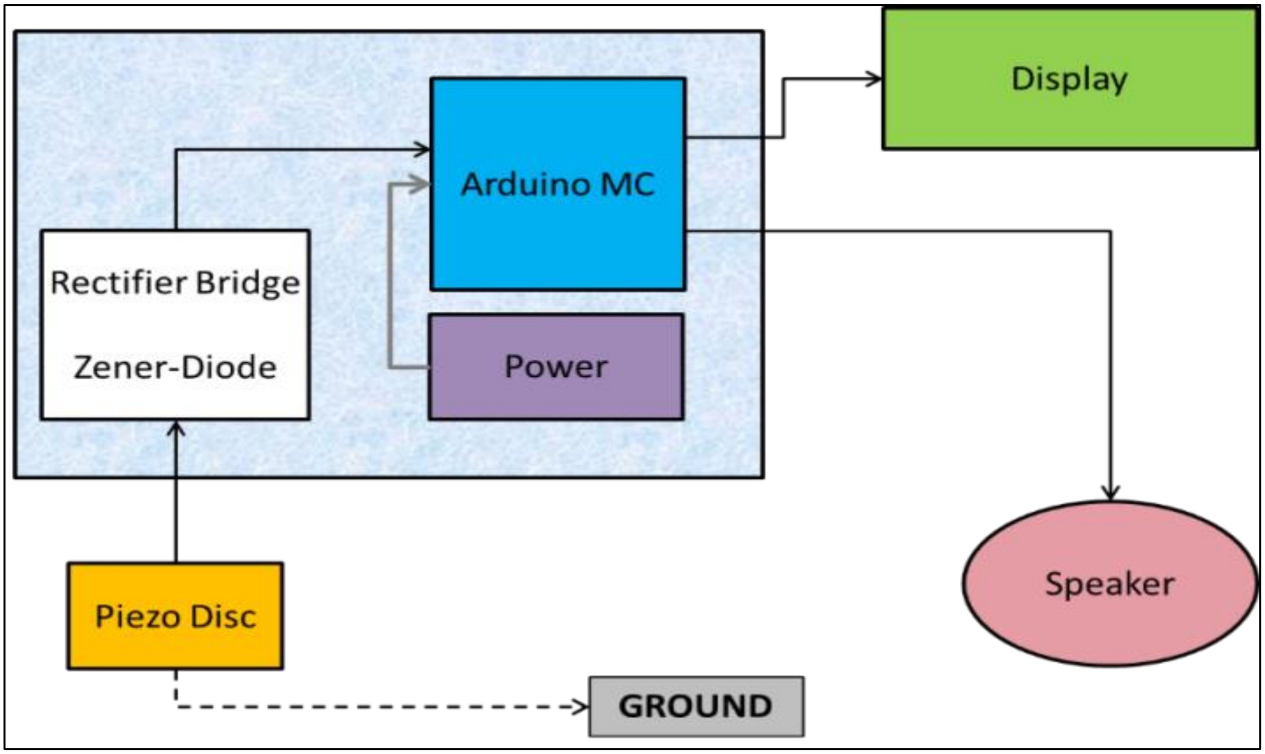
Arduino©. (2013). Retrieved April 10, 2013 from: http://www.arduino.cc/

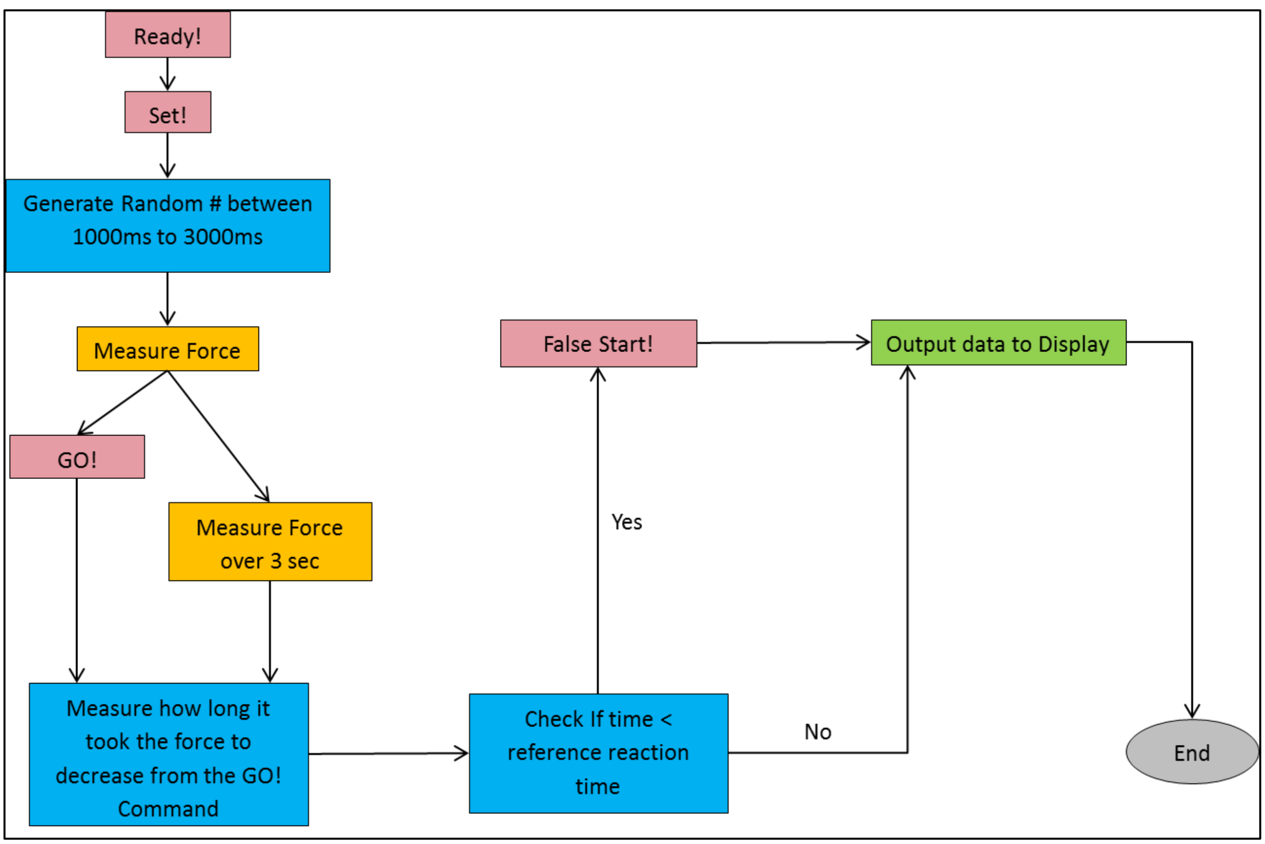
International Association of Athletics Federations. (2012). The Referee. Retrieved April 1, 2013 from: http://www.iaaf.org/aboutiaaf/documents/technical#manuals-guidelines

Appendix D: MICROCONTROLLER FLOWCHART AND SCHEMATIC

This appendix contains the schematic and procedural flow-chart for the microcontroller. Both were created during the Capstone project and revised for the thesis project [1]. The original schematic only described the use of one sensor, while in the thesis, that was duplicated for the implementation of a second sensor as well.

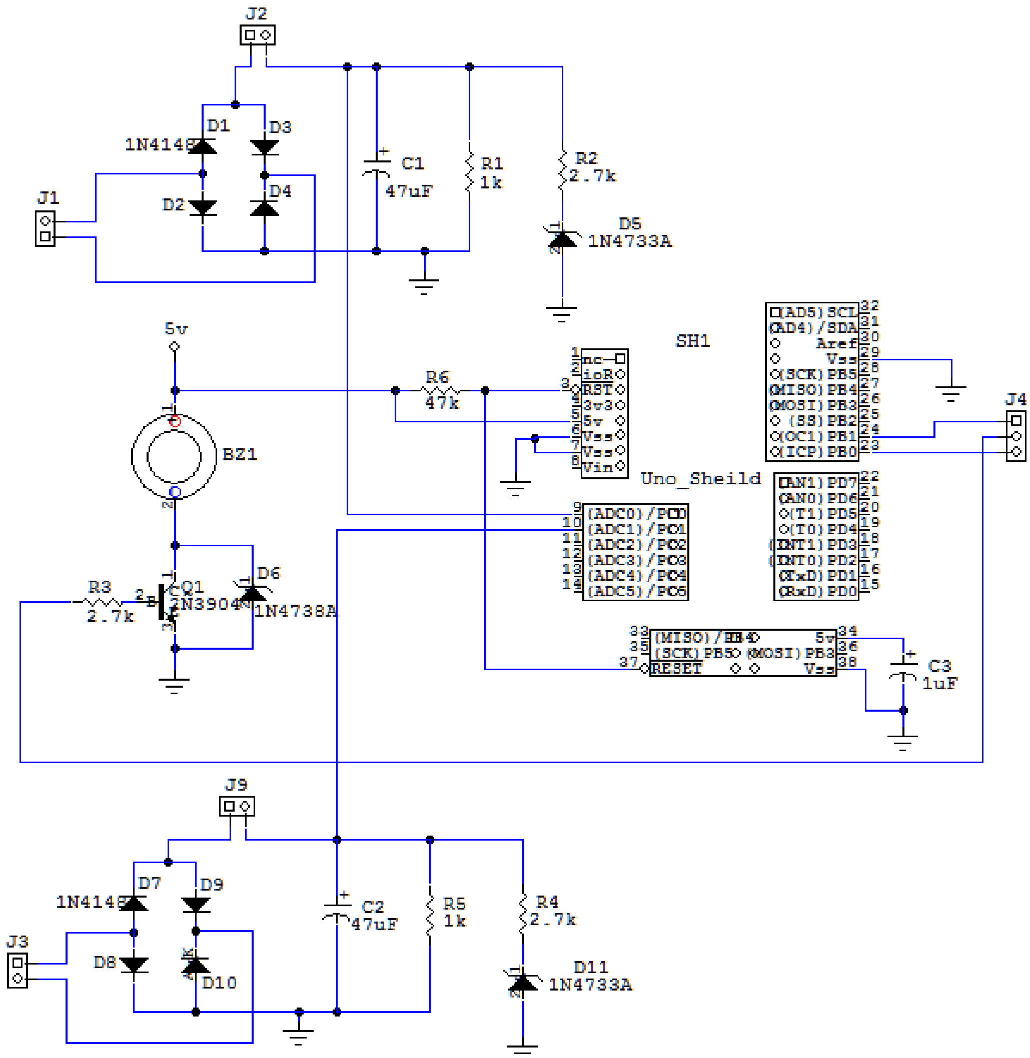
The flow chart described here from the Capstone project also was revised for this thesis. For instance, code was added to also collect data between the “SET” and “GO” commands as well in order to detect false starts prior to the starting gun. The randomization of the delay between “SET” and “GO” was also updated based on input from coaches to reflect more realistic delays so that sprinters are not caught off guard thus ruining their sprint start.


Display
Arduino MC
Rectifier Bridge
Zener-Diode
Power
Piezo Disc
Speaker
GROUND


Ready!
Set!
Generate Random # between 1000ms to 3000ms
Measure Force
GO!
Measure Force over 3 sec
Measure how long it took the force to decrease from the GO! Command
Check If time < reference reaction time
Yes
No
False Start!
Output data to Display
End

Appendix E: CIRCUIT DIAGRAM OF PIEZO-SENSOR BOARD

The circuit and the circuit schematic for the piezo-sensor and Arduino board configuration was done by the Electrical Engineering Lab Technician, Rob Thomson. Due to the limitations of the Arduino Uno board, a Zener diode, rectifiers, and resistors needed to be incorporated in the connection between the piezo sensors and the board. The Zener Diode was in place to ensure the sensor output was capped at 5.0V. The resistors and the rectifier ensured that the AC voltage generated by the sensors' vibrations is converted into a DC impulse voltage. An RC circuit also needed to be incorporated on the board since it was found after initial tests that there was residual charge in the Arduino pins from the sensors affecting the readings. The RC circuit drained the residual charge quickly, acting as a filter so the Arduino would only read the voltages generated by sensor without residual noise.


J2
J1
D1
D3
D2
D4
1N4148
C1
47uF
R1
1k
R2
2.7k
D5
1N4733A
5v
R6
47k
BZ1
SH1
Uno_Sheild
J4
R3
2.7k
Q1
2N3904
D6
1N4738A
C3
1uF
J9
J3
D7
D9
D8
D10
1N4148
C2
47uF
R5
1k
R4
2.7k
D11
1N4733A
nc
ioR
RST
3v3
5v
Vss
Vss
Vin
(ADC0)/PC0
(ADC1)/PC1
(ADC2)/PC2
(ADC3)/PC3
(ADC4)/PC4
(ADC5)/PC5
(AD5)SCL
(AD4)/SDA
Aref
Vss
(SCK)PB5
(MISO)PB4
(MOSI)PB3
(SS)PB2
(OC1)PB1
(ICP)PB0
(AN1)PD7
(AN0)PD6
(T1)PD5
(T0)PD4
(INT1)PD3
(INT0)PD2
(TxD)PD1
(RxD)PD0
(MISO)/PB4
5v
(SCK)PB5
(MOSI)PB3
RESET
Vss

Appendix F: IMPACT HAMMER TEST PHOTOS

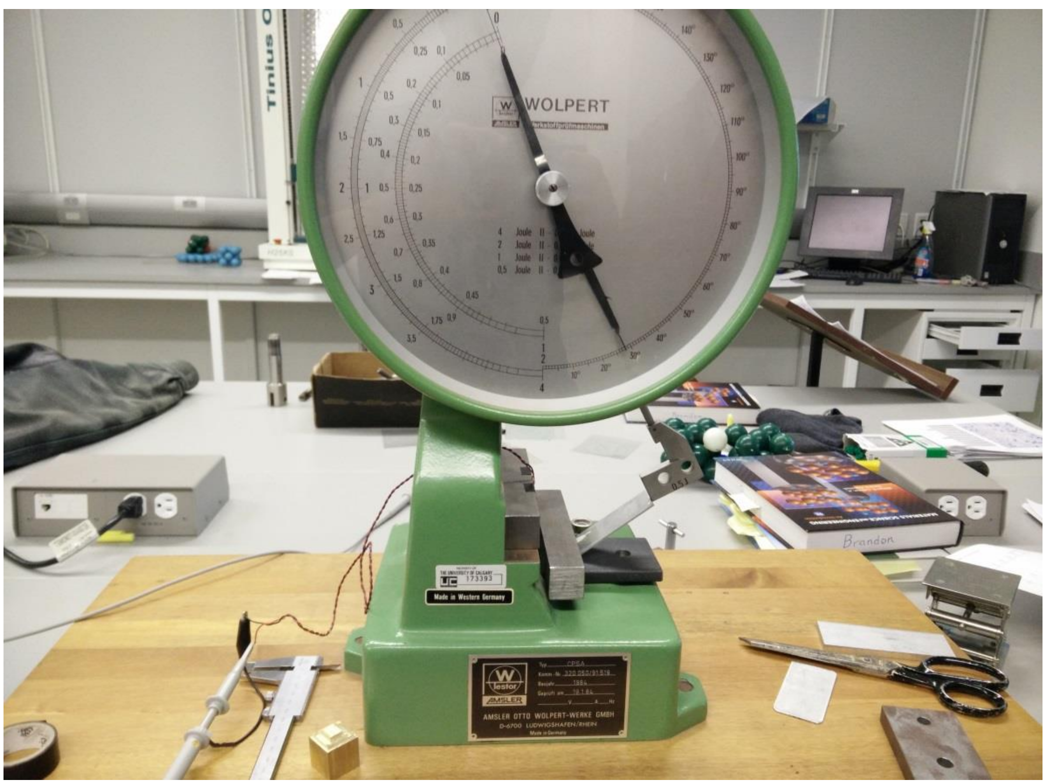
In this section, I show some of the photos taken during the impact hammer test of the sensors that display the apparatus setup and the testing methodology. Since this is a very unique project, the setup of the impact hammer device had to be adapted to test the sensors. As such, the sensors were mounted on a metal block using electrical tape the thickness of which was measured to be 0.15mm.


0,5 Joule
0,45
0,9
0,5
1
2
4
10°
20°
30°
40°
50°
60°
70°
0,5 J


PROPERTY OF
THE UNIVERSITY OF CALGARY
173393
Made in Western Germany
0,5 J
Typ CPSA
Komm.-Nr.


PROPERTY OF
THE UNIVERSITY OF CALGARY
173393
Made in Western Germany
0.5 J

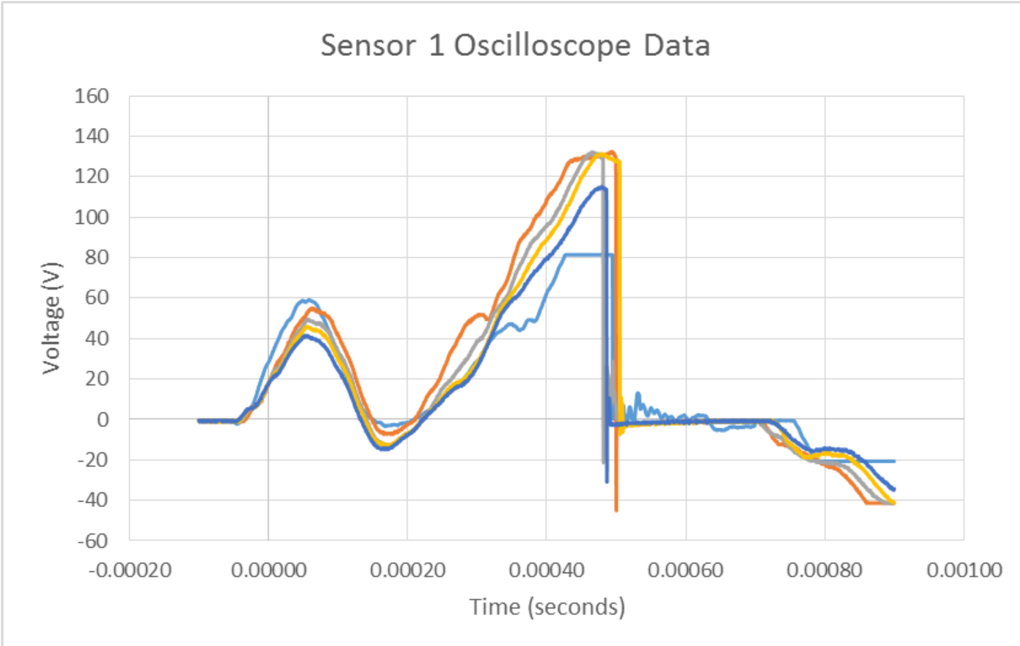

WOLPERT
Made in Western Germany
AMSLER OTTO WOLPERT-WERKE GMBH
D-6700 LUDWIGSHAFEN/RHEIN
Brandon

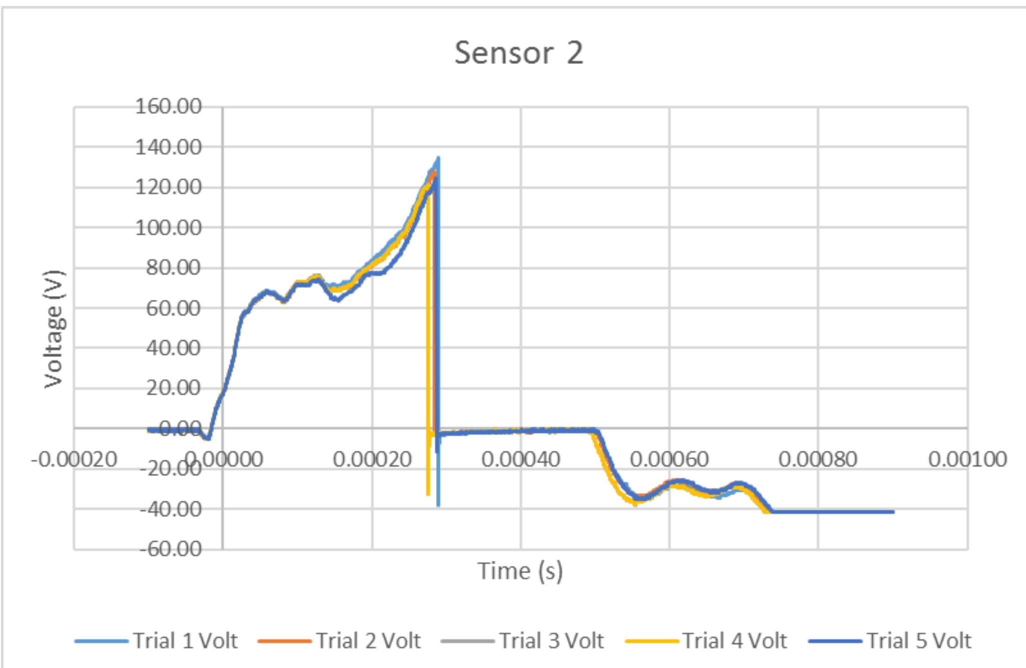
Appendix G: OSCILLOSCOPE DATA FROM IMPACT HAMMER TESTS

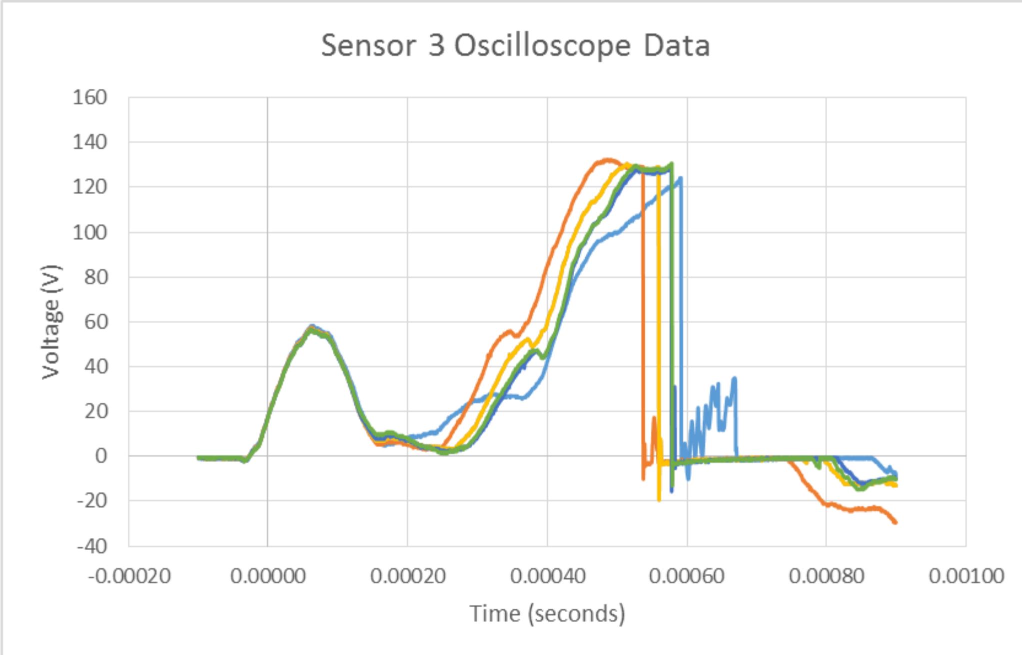
Due to the nature of piezo-discs, their sensitivity varies based on the cut of the crystal in the disc. The orientation of the grain, manufacturing defects or product defects can impact the voltage the discs' output for a given vibration or impact. Having this knowledge, an impact hammer machine was used to test a set of 10 disc sensors in order to find two sensors having similar amplifications and consistency to implement in the blocks for data collection. The experiment set up, as seen in Appendix F was rudimentary, yet provided reliable and repeatable results. As seen from the graphs below, sensors numbered 1 and 3 showed consistent data that was similar in peak amplitude voltages. They were chosen to be placed in the blocks for the actual experiments.

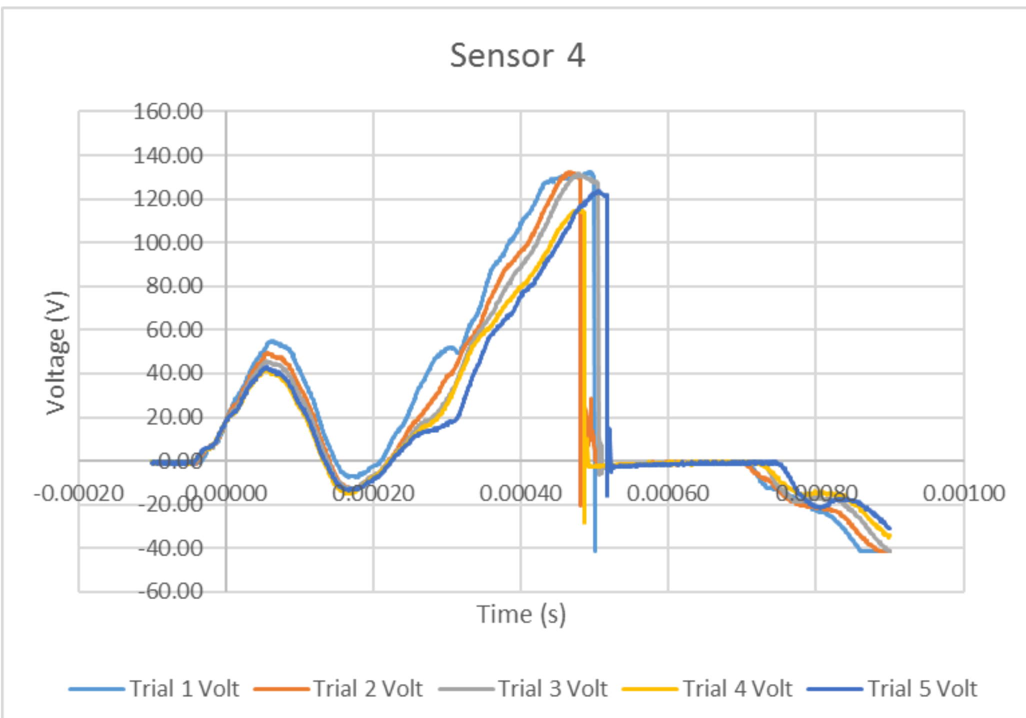
A further impact hammer test was performed to determine whether the orientation of the sensors (how the leads were oriented) would affect the output from the sensor. The sensor was positioned and rotated to have the leads oriented in either North or East directions. It was determined that this orientation change did have an effect on the data, however it was further determined that this is prevalent and uniform across all the sensors. As such it was determined that further to finding two sensors with similar amplifications, placing the sensors in the blocks in the same manner was also important for consistent and non-biased data.

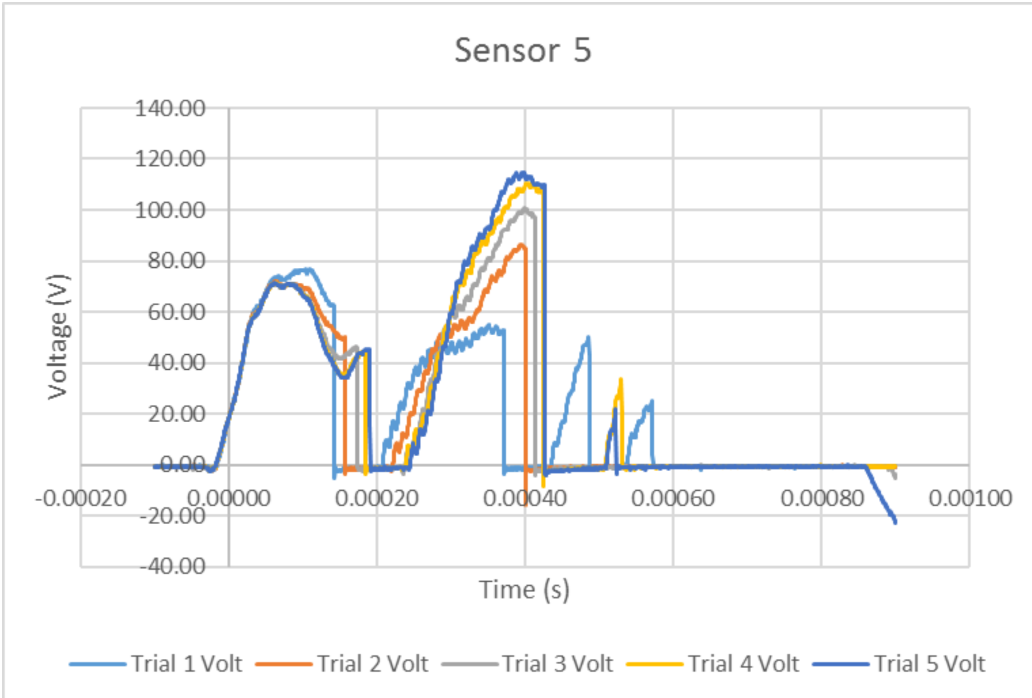
From this test, focusing on the first peak, sensors 1 and 3 were chosen for their consistent outputs, as well as similar voltage readings which ensured uniformity in the data collected from both of the sprinter's feet. The second peak can be ignored since it corresponds to the impact hammer rebounding on the sensor after the first hit. This is also why the oscilloscope voltage decays instantly to zero after the second peak, since the impact hammer is now resting on the sensor. If one or both of these sensors failed during the data collection phase, then this impact hammer test would have to be re-conducted with a new set of sensors since none of the other sensors seem to match sensors 1 and 3 in this set.

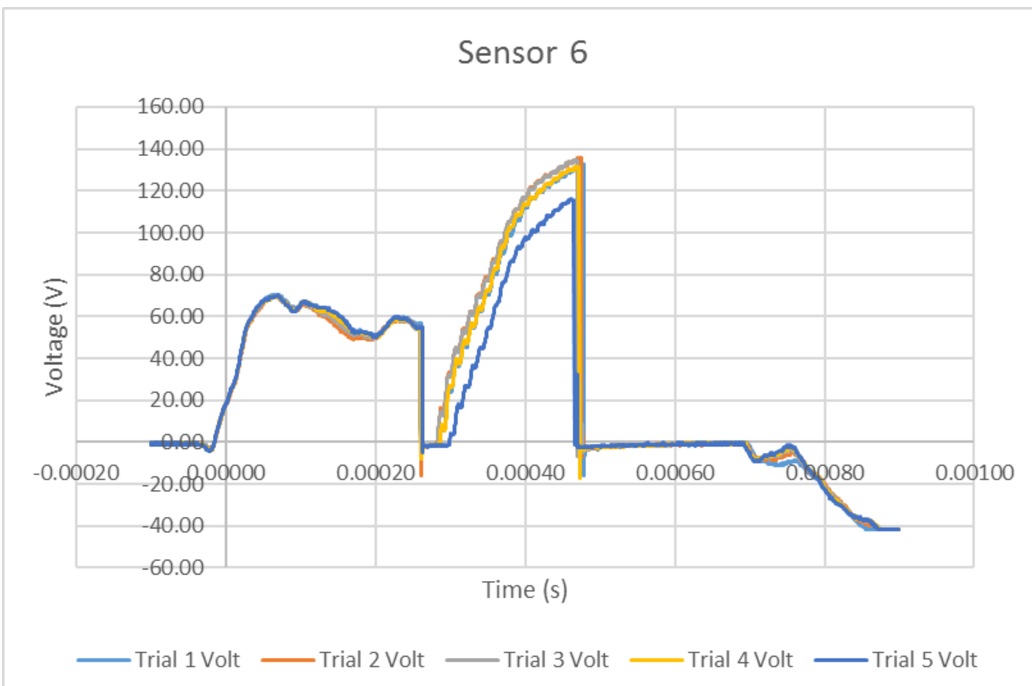

Sensor 1 Oscilloscope Data
Voltage (V)
Time (seconds)
160
140
120
100
80
60
40
20
0
-20
-40
-60
-0.00020
0.00000
0.00020
0.00040
0.00060
0.00080
0.00100

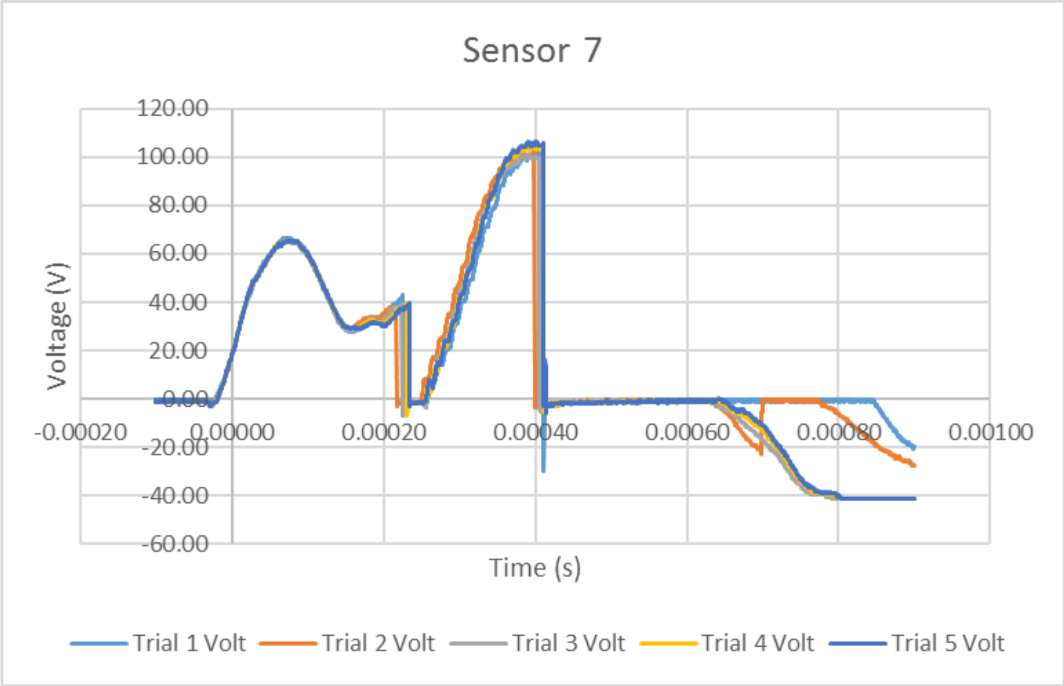

Sensor 2
Voltage (V)
Time (s)
160.00
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00
-0.00020
0.00000
0.00020
0.00040
0.00060
0.00080
0.00100
Trial 1 Volt
Trial 2 Volt
Trial 3 Volt
Trial 4 Volt
Trial 5 Volt

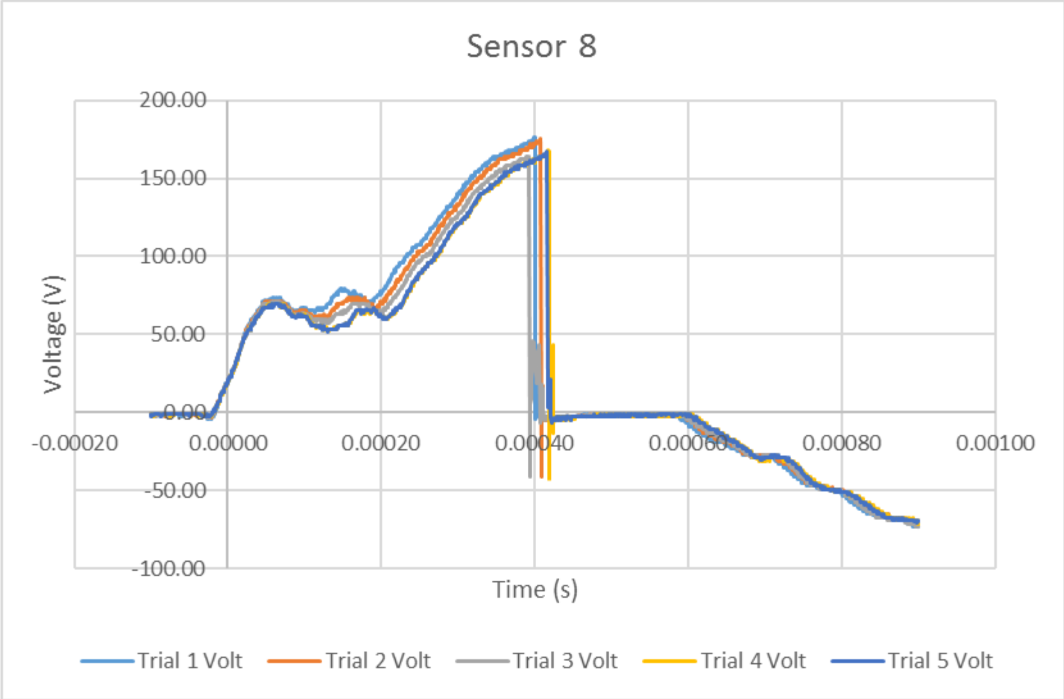

Sensor 3 Oscilloscope Data
Voltage (V)
Time (seconds)
160
140
120
100
80
60
40
20
0
-20
-40
-0.00020
0.00000
0.00020
0.00040
0.00060
0.00080
0.00100

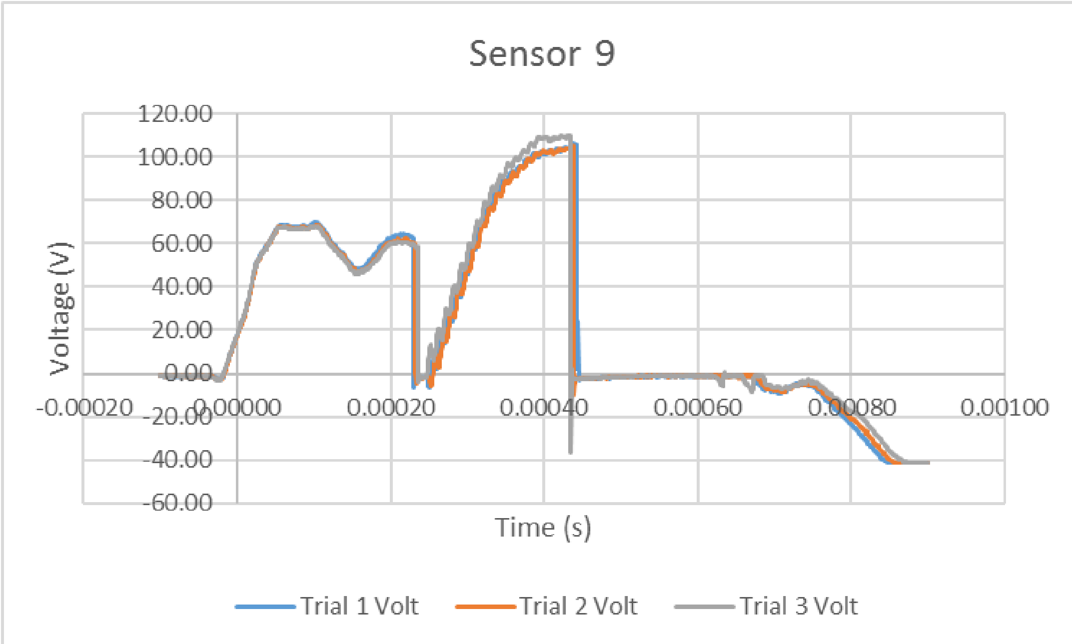

Sensor 4
Voltage (V)
Time (s)
160.00
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00
-0.00020
0.00000
0.00020
0.00040
0.00060
0.00080
0.00100
Trial 1 Volt
Trial 2 Volt
Trial 3 Volt
Trial 4 Volt
Trial 5 Volt

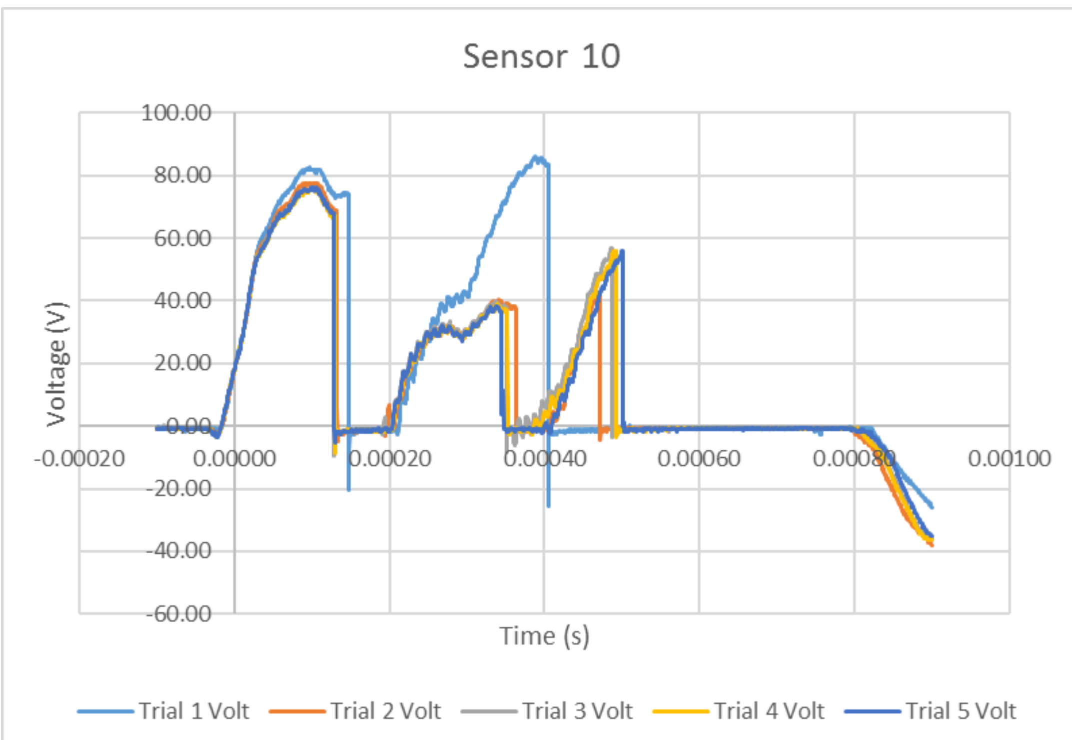

Sensor 5
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
-20.00
-40.00
Voltage (V)
-0.00020
0.00000
0.00020
0.00040
0.00060
0.00080
0.00100
Time (s)
Trial 1 Volt
Trial 2 Volt
Trial 3 Volt
Trial 4 Volt
Trial 5 Volt


Sensor 6
160.00
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00
Voltage (V)
-0.00020
0.00000
0.00020
0.00040
0.00060
0.00080
0.00100
Time (s)
Trial 1 Volt
Trial 2 Volt
Trial 3 Volt
Trial 4 Volt
Trial 5 Volt


Sensor 7
Voltage (V)
120.00
100.00
80.00
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00
-0.00020
0.00000
0.00020
0.00040
0.00060
0.00080
0.00100
Time (s)
Trial 1 Volt
Trial 2 Volt
Trial 3 Volt
Trial 4 Volt
Trial 5 Volt


Sensor 8
Voltage (V)
200.00
150.00
100.00
50.00
0.00
-50.00
-100.00
-0.00020
0.00000
0.00020
0.00040
0.00060
0.00080
0.00100
Time (s)
Trial 1 Volt
Trial 2 Volt
Trial 3 Volt
Trial 4 Volt
Trial 5 Volt


Sensor 9
120.00
100.00
80.00
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00
Voltage (V)
-0.00020
0.00000
0.00020
0.00040
0.00060
0.00080
0.00100
Time (s)
Trial 1 Volt
Trial 2 Volt
Trial 3 Volt


Sensor 10
100.00
80.00
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00
Voltage (V)
-0.00020
0.00000
0.00020
0.00040
0.00060
0.00080
0.00100
Time (s)
Trial 1 Volt
Trial 2 Volt
Trial 3 Volt
Trial 4 Volt
Trial 5 Volt

Appendix H: COACH CHECKLIST FOR EVALUATING SPRINT STARTS

In this appendix, I detail the primary and the revised checklist used by coaches to grade the sprint starts and assign performance scores. The first checklist is the one used for this study, while the second checklist is the revised version developed with the help of the NCCP. The revised checklist contains additional information and criteria for judging the athletes “On your marks” and Set” position postures as well as estimating knee, ankle, and hip angles during the sprint start. Since these components were not measures as part of this study, it was hypothesized that changes in these parameters would result in a noticeable difference on the forces measured at the blocks. The exact correlation between these parameters and the data collected from the blocks is subject to further analysis and future research.

Coach Performance Feedback:

Coach Name:
Coach Email:

Athlete Sex:
Athlete Height:
Athlete Weight:

Video File #:

30m time: _________ seconds

Performance score: / 10

Feedback:

- What was good about the start?
- What was bad about the start?
- What did the coach look for to evaluate the start (posture, push-off angle, etc.)?
- General comments …

Shoulders above line? _______

Head hangs loose? _______

First move arm? _______

Arm drive long and low? _______

Foot pulled along shin? _______

First step short and fast? _______

Start Block Technical Model

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Check list:

On your Mark:

- Feet on the block with toes touching the track
- Knee of rear leg in contact with the track
- Hands shoulder width apart, just behind the line ensuring equal placement on either side of the line through the block –shaft
- Shoulder down and head held high
- Thumb and fingers forming a high bridge to produce high shoulders
- Arms are fully extended
- Weight equally distributed between the legs and hands
- Eyes focused 10 cm in front of the line
- Head in natural alignment with the body
- Knees pointing down the track
- Cue: comfortable and balanced

Set:

- Commences when athletes stop moving - all athletes must be still before the starter will move the athletes to set
- Hips elevated in a controlled, steady movement
- **Rear knee angle is about 140 degrees**
- **Front knee angle is about 110 degrees**
- **Angle   90 degree angle (dorsi flexed)**
- The center of gravity will shift forward more with stronger athletes (developmental point)
- Head in natural alignment, eyes looking down
- Cue: Balanced, Clear head to listen to the gun to **REACT !**

Gun:

- Hand quickly lifted from the track
- Hand on the same side of the front foot leads the head forward out of the blocks
- Opposite arm is driven upwards
- Quick and powerful drive from the legs, getting the rear thigh through fast
- Drive for the blocks, keeping a quick low foot recovery
- Maintain body lean, while driving from blocks
- Complete flexion of the rear leg as it is pulled through
- Foot dorsiflexed, about 3 -5 cm above the ground
- Cue: On gun **REACT** with Back Leg and Opposite arm