Functional Mechanical Assessment of Foot and Ankle Stiffness and Work Production in Ice Hockey Skate Boots

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Statement of Originality

All material presented in this thesis contains original work completed by the author, except where noted via references indicating outside contributions. It is the belief of the author of this thesis that the material presented significantly contributes to the topic of kinematic analysis in ice-skating using motion capture cameras and a Biodex Dynamometer as methods of comparison and analysis.

Acknowledgements

I would like to take thank some of the people who made it possible for me to complete this thesis project. Firstly, I would like to thank my supervisor, Dr. David Pearsall, who was always available to answer any questions I may have had and whose experience and guidance made the toughest stretches of this project easier to handle.

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Abstract

Ice hockey is a sport characterized by high speeds, sharp turns and abrupt stops. As a result of these explosive and agile movements, the interaction of the foot and ankle with the skate boot is fundamental for optimal stability and propulsion. The purpose of this study was to determine the nature of this mechanical coupling in both a conventional and prototype skate models. In phase one, a Biodex System 4 Pro dynamometer was used to isolate the foot and ankle / boot dynamics in sagittal and frontal plane movements. Three footwear conditions were evaluated (control shoe, a skate boot in production and a modified skate boot prototype). In phase two, lower body kinematics were assessed using 3D motion capture to determine if the above skate models would yield different joint movement coordination during skating push-offs using the two skate boot models.

When comparing the three foot conditions, there was a significantly greater range of motion observed in the shoe control and modified skate boot than the regular skate boot (65.2° vs. 52.4° vs. 35.7°, $p < 0.05$). The total work done was only significant in the shoe control over the regular skate boot (16 kJ vs. 8.9 kJ, $p < 0.05$). In phase two, only the maximum plantar flexion was greater with the modified skate (11.3° vs. 1.3°, $p < 0.05$).

The biodex dynamometer was able to discern differences between the three types of footwear using the dependent variables selected. Using a combination of the

active and passive modes, this system has provided a valuable measurement of quantifying boot stiffness characteristics.

Abrégé

Une vitesse de jeu rapide, les virages brusques ainsi que les arrêts soudains sont des caractéristiques bien particulières au hockey sur glace. Considérant ces mouvements explosifs et agiles, l'interaction entre le pied, la cheville ainsi que la botte du patin devient fondamentale pour obtenir une propulsion et une stabilité optimale. Le but de cette études était de déterminer la nature cette interaction mécanique pour un modèle de patin a glace conventionnel ainsi que pour un prototype. Dans un premier temps, un dynamomètre Biodex System 4 a été utilisé pour isoler de façon dynamique le pied et la cheville/patin dans les plans sagittal et frontal. Trois conditions expérimentales ont été évaluées (soulier contrôle, patin commercialisé ainsi qu'un patin modifié). Par la suite, la cinématique des membres inférieurs fut mesurée en utilisant une système de capture du mouvement pour déterminer si les différentes botte de patin affecteraient la coordination motrice lors d'un départ.

En comparant les trois conditions de botte, une différence significative a été observée pour l'amplitude de mouvement entre le soulier et le patin modifié et le patin commercial (65.2° vs. 52.4° vs. 35.7°, $p < 0.05$). Le travail total était seulement significatif entre le soulier et le patin commercial (16 kJ vs 8.9 kJ, $p <$ 0.05). Pour la deuxième phase, seulement la flexion plantaire maximale était plus

grande avec le patin modifié 11.3° vs. 1.3°, $p < 0.05$).

Le dynamomètre Biodex a pu clairement discerner des différences entre les différentes conditions de botte pour les variables dépendantes sélectionnées. En utilisant les modes passifs et actifs, le système a permis de générer une méthode de quantification caractéristique de la rigidité de bottes.

Contribution of Authors

This thesis will be co authored, in order, by Dr. David Pearsall, Dr. Rene Turcotte and Dr. Taivassalo. I was responsible for setting up the protocol for both phases of the project, along with data collection and processing, statistical analysis, generating and/or adapting figures and writing of the related chapters. Dr. Pearsall provided ideas for the protocol and set up of the platform in the second phase of the project as well as comments on the final draft of the thesis. Dr Turcotte provided insights for the statistical analysis and feedback on the protocol. Dr. Taivassalo provided the use of her laboratory space and the Biodex dynamometer.

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Definitions/Illustrations

Plantar-flexion: Movement of the ankle joint along the sagittal plane away from the proximal joints of the body.

Figure 1: Side view of the ankle foot complex in plantar-flexion, set up in the Biodex Dynamometer

Dorsi-flexion: Movement of the ankle joint along the sagittal plane toward the proximal joints of the body.

Figure 2: Side view of the ankle foot complex in dorsi-flexion

Neutral Foot (Plantar-flexion): The angle defined as in between maximum dorsi-flexion and plantar-flexion.


Figure 3: Side view of a neutral position of the ankle foot complex

Inversion: Movement of the ankle joint along the frontal plane toward the midline of the body.


Figure 4: Top view of the inverted ankle foot complex

Eversion: Movement of the ankle joint along the frontal plane away from the midline of the body.


Figure 5: Top view of the everted ankle foot complex

Dynamometer: A device used to measure torque and velocity, powered by a motor and an interacting lever arm.

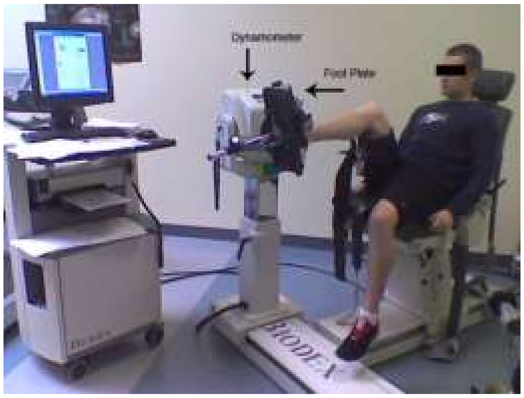

Figure 6: Biodex Dynamometer set-up

Torque: The force x length product, in Newton-meters (N.m), that tends to rotate an object. In this project, it will describe the mechanical effort exerted by the muscles to create (or passive resistance by the combined foot and ankle complex plus hockey boot) joint rotation about an anatomical axis (ankle for plantar/dorsiflexion; subtalar for inversion/eversion). Peak torques can be found for each repetition on the Biodex machine.

Range of Motion (ROM): defined, in degrees, as the difference between the maximum and minimum values in the position channel on the Biodex dynamometer.

Work: defined, in kilojoules (kJ) , as the area under the curve of the torque vs. position plot.

1. Chapter 1 - Introduction

1.1 Thesis Outline

This thesis will focus on the use of a Biodex dynamometer to characterize boot stiffness properties comparing two skate boot types: a Bauer One95 model skate boot and a modified skate boot with a flexible tendon guard. A Nike Free 5.0 will be used as a control shoe in the comparisons. A second phase of the project will compare the results from a skating push off done on a synthetic ice surface to the results obtained from the Biodex dynamometer in phase one. Chapter one will provide a background into the classification of skating skills required in the sport of ice hockey. It will also provide an overview of dynamometers and their uses in therapy. Chapter two will list the dependent variables, methodologies and statistical tests to be used in the research. Chapter three will discuss the implications of the results of this study and chapter four will list the references used in this thesis.

1.2 Introduction/Rationale

Ice hockey is a sport characterized by explosive starts and stops as well as skating agility including movement tasks such as rapid changes in direction and tight turns, so as to avoid obstacles or visually misdirect opponent players of your intended objective, also known as dekes. However, kinematics of these movements are not easy to decipher due to the large surface area required to demonstrate the skills along with additional limitations of cooler temperatures on ice surfaces (Upjohn et al., 2008). These limitations are further amplified when analyzing the interactions between the skater's foot and the skate boot due to an extremely constricted working space.

A possible solution to these limitations would be to analyze the movements in question by isolating them from the environment. This would allow experimenters control of specific variables of the movement or skill in a laboratory setting. A Biodex System (Biodex System 4, Shirley, NY, USA) allows the experimenter to examine in detail, the kinematics of movements in a limb joint by isolating it from the rest of the body's joints. The experimenter can also manipulate aspects of the limb interaction with the environment by adding attachments or modifying shoe components to emulate conditions of a specific sport. This thesis will outline the methods used to analyze the kinetics of two different skate boots using a dynamometer. The skate boots being analyzed are the Bauer One95 and a modified skate of the One95 model in which the tendon guard has been given more flexibility, along with a running shoe as a control foot condition. The quantitative measures for the boots will be compared to a shoe control, simulating a free ankle joint. In addition, a second aspect of this study will compare the upper joint kinematics of the same two boot models in a push off stride on a synthetic ice surface.

1.3 Classification of Skating Skills

While the skating mechanics of ice hockey players are similar in motor patterns to speed and figure skating, the tasks required of hockey players during a game such as starting, accelerating, stopping and changing directions by reacting to the game, require a substantially different skill set. This also leads to divergent skate designs that interact with the foot in different ways than would be apparent in research related to speed or figure skating.

Skating on ice is a unique form of travel for humans in comparison to walking or running, the force of friction cannot be applied in the direction opposing motion. In addition, due to a low coefficient of friction between a metal skate blade and the ice surface, sufficient push-off forces cannot be achieved in the direction parallel to the length of the blade. As a result, hockey players achieve higher frictional forces by orienting the skate blade perpendicular to the plane of the ice by rotating the hip externally, pronating the trailing foot, and pushing off laterally. A 45-degree angle between the skate blade and the ice provides additional support during the push off phase by using the sharp inside edge of the skate blade (Pearsall et. al, 2000).

1.3.1 Forward Skating

Since the game of hockey requires quick acceleration to get to a point in the rink for several hockey-related tasks, efficiency in mobility on ice is of prime importance to hockey players. As a result, research is warranted in the area of skating kinematics in hockey.

Early research into hockey skating showed that a stride is biphasic with a support phase and swing phase. The support phase further consists of the glide and push off phase. Both the support and swing phases have components of single-support and double limb support (Marino & Weese, 1979). Most of the propulsion in the push off phase takes place soon after the propulsive skate leg is rotated outward while the knee and ankle are extended. These joint movements are necessary to allow grip on the ice for traction (Behm et. al, 2005). During the swing phase, the recovering/back skate is brought back under the center of mass and contact is made with the ice surface. Once this happens, the skater is said to be in the glide phase. When the propulsive/front skate is nearing the end of its range of motion, it enters the push off phase. This glide phase lasts about as long as is needed to recover the back skate and laterally rotate it to begin applying force. This decreases the time required to swing the recovering skate forward and is associated with higher skating speeds (Marino et. al, 1977).

In a separate study done by Marino et. al (1978), skating speed was dependent more on stride frequency and glide phases than stride length. In addition, higher speeds correlated with a shorter double support phase and an increased stride frequency. The same study also showed that at lower and medium speeds, skaters were more upright in their stance with a longer stride, whereas at high speeds, skaters brought the recovery leg forward much faster to recover for the next stride.

Research on skating acceleration showed that acceleration occurs in both double and single support phases. However, the temporal length of the acceleration varied between the two phases as it occurred throughout the double support but only for about half of the single support phase (Marino & Weese, 1979). After the first 1.75 seconds of skating, the first period of negative acceleration occurred. From this point on, the skaters undergo a period of acceleration and deceleration when skating at full speed.

While most of these studies have analyzed the kinematics of hockey skating in detail, few studies have focused on the relationship between the skate boot and the foot. Pearsall et. al (2000) looked at the ankle kinematics during skating using an ankle goniometer, measuring angles in the sagittal plane. The results of this study showed that, during acceleration the total angular displacement between the motions of dorsi-flexion and plantar-flexion increased until maximum velocity was achieved. Maximum ankle inversion coincided with the swing phase of the skating stride, while maximum ankle eversion occurred at push-off (Pearsall et. al, 2000).

1.3.2 Backwards Skating

Backwards skating is another important component of a hockey player's skill set and one that is also quite different from speed skating because it involves movement in the backwards direction while facing an oncoming opponent or hockey puck. As a result, ice hockey blades have a functional feature that also makes it different from speed skates. Since ice hockey skates are high cut to allow for lateral stability, this typically results in a reduced range of motion in dorsi/plantar-flexion movements. This prevents the ankle from bending in ways that would allow for compensation and balance maintenance when skating backward. Ice hockey blades thus feature a longitudinally curved blade (front to back), in contrast to the mostly flat blades of speed skates. This 'rocking' design on the blade is useful in skating backward as it allows the center of mass to shift laterally from side to side while skating backward.

In forward skating, a player bends at the hips and leans forward in the direction of motion when skating at high speeds. However, in backward skating this is not possible as it would most likely lead to the skater losing balance and falling backwards. Due to this, skaters must bend deeper at the hip and knee joints. Propulsion is still established with the force applied transversely in relation to the edge of the skate blade. Also, in backward skating, the orientation of the skate blade is forward and pointing laterally, when viewed from the skater's perspective, much like forward skating. However, the hip is rotated internally to provide the push off forces, as opposed to an external rotation in forward skating. In the analysis of backward skating mechanics, smaller ranges of motions have been observed at the joints, resulting in lower skating velocity. To compensate for this, most hockey players skate forward initially to build up speed and then spin on the skate blade to resume skating backwards with a higher initial velocity (Pearsall et. al, 2000).

1.3.3 Turning

Turning sharply to avoid body checks, follow the motion of a puck or get into an open space on the ice are all important reasons for a hockey player to be able to turn efficiently in hockey skates. In order to turn on ice, angular movements usually occur around an external axis on ice or about the player's axis. If the turn is to occur about the player's axis, it is accomplished by planting one skate blade perpendicular to the ice surface while the other skate blade acts as a pivot point to spin around on by leaning into the desired direction of motion.

1.3.4 Starts and Stops

Starting and stopping on ice most importantly dictate how quickly a player can get to a point on the ice or make quick changes in direction. Starting from a stopped position in the game of hockey requires as short a time to get to maximum velocity as possible. Stopping, on the other hand, requires the shortest distance and time to come to near complete or complete stop by reacting to the game and making appropriate adjustments..

Hockey starts are generally performed in three ways: Forward start, Crossover start and side/T start. The first of these starts, the forward start is most similar to speed skating and has more research analyzing its kinematics than the other starts.

In a forward start, the skate blade pushing off is nearly perpendicular to the direction of motion in order to get sufficient grip from the ice surface. Research on forward starts in speed skating showed that the frequency of repeatedly bringing the recovery leg forward and into propulsion contributed more to peak velocity than did the strength of the push off (de Koning et. al, 1993).

In addition, one study devised regression models to outline and characterize the factors important in completing an efficient front start. Results showed that a high stride rate, an increased forward lean, a truncated take off angle and placing the recovery skate directly beneath the center of mass just as the double support phase begins were critical for optimizing front start execution (Marino &Weese, 1979). Recent research on two groups of sprint skating athletes and well trained skaters corroborated this model as the authors found that the elite athletes were able to position their centre of mass closer to the starting line and starting block than the well-trained sprinters. This is important because the athlete can create greater velocity of his center of mass. This was accomplished by having the shoulders further forward which allowed the rear knee angle to be greater than those observed in the starting position of well-trained sprinters (Slawinski et. al, 2010).

The most common stop employed by hockey players is the parallel stop with both skates quickly turned perpendicular to the direction of travel along with a slight lean backwards to counter the intertia of traveling forwards at a high velocity. The lean also facilitates the edges of the skate blade to dig into the ice and shaving some of it off in the process of stopping. Analysis of the skating stop reveals that to achieve a quick perpendicular turn in motion, both skates are laterally flexed while quickly turning horizontally. The skate closest to the body also typically has a lower flexion angle than the leading skate (Gagnon, Dore & Lamontagne, 1983).

Biomechanical analysis of skating has shown that professional skaters have a lower pre-extension knee angle and a greater amount of work per skating stroke. They also had a higher knee extension velocity, pushing into the ice at a greater horizontal push off, for a shorter time. In the push off phase of skating, the knee extensors pre-stretch at the same time that the flexors activate. This allows for potentiation of the torque produced at the moment of push off. However, in stiffer boots, the knee was lifted off the ice a lot before the knee was extended fully and this was attributed to the boot preventing full plantar flexion (de Boer et. al, 1987). Another study cited that skating step length was not a valid measure of skating speed but rather, it was a greater range of motion at the ankle and the knee along with the rate of steps (McCaw & Hoshizaki et. al, 1987).

One would assume that greater flexibility in the joints of skaters and certain anthropometric characteristics might provide an advantage in skating speed. Song and Reid (1993) analyzed the length of levers of the leg and the girth of anatomical segments to find if a correlation exists with skating speed. The results showed that the anthropometric data was correlated with limb girth but not with skating speed, suggesting that body shape was not important in predicting maximum skating speed. There was also no significant correlation with leg strength and skating speed. These results suggest that more importance should be placed on developing good skating technique and using well-designed skates.

1.4 Skate Design

From its innovations in the 1880s, the sport of hockey, along with the equipment required to play has become more technologically advanced. The design and materials used for the ice hockey boot have also changed and advanced over the years (Pearsall & Turcotte, 2007). The figure below illustrates the parts of a skate boot in a modern ice hockey skate (Figure 7).

Figure 7: Structural components of a hockey skate (adapted from Pearsall and Turcotte (2007).

Hockey skates consist of a toe box, a heel counter, Achilles guard, metal blade, rigid sole, skate blade housing and a cushioned tongue. Early skate blade housing was made of a wooden block. This involved into an all-metal assembly, which added weight to the skates and reduced overall speed but increased stability and longevity. In the 1960s and 70s, a hollow plastic skate blade housing composed of a mixture of polyethylene, fibreglass and resins was introduced. This provided support with a reduction in skate weight, thereby helping skaters achieve higher velocities with more manoeuvrability (Pearsall & Turcotte, 2007).

In addition to the skate blade holder, the skate boot itself can vary in materials used, from early models featuring leather to more recent Kevlar and graphite compositions, depending on the skate model. Recent designs have included a moulded boot of hard plastic designed to withstand the stresses of errant sticks, pucks and other hard objects. Other skate designs that have an influence on figure skating performance include blade sharpness, radius of curvature and blade thickness and taper. As mentioned earlier, the radius of curvature of the blade facilitates a smoother backward skating stride and better balance in overall movements. Skaters prefer a sharp blade to provide them with the traction and stopping power needed on ice. However there is an optimal level of sharpness that balances the ability to dig into the ice and the ability to stop smoothly. To further exaggerate the inside and outside edges of the skate blades, there is a hollow portion within the blade that leads out to either blade edge. During the push off phase, the inside edge is angled toward the ice surface, allowing it to cut into the ice. During stopping and turning, the outside edges are used for grip. The following figure (Figure 8) illustrates this concept by demonstrating the direction of the force vectors applied by the skater and those applied by the ice surface. Both are important in maintaining grip and balance as the skater leans away from the center of mass to turn, stop, accelerate, etc.

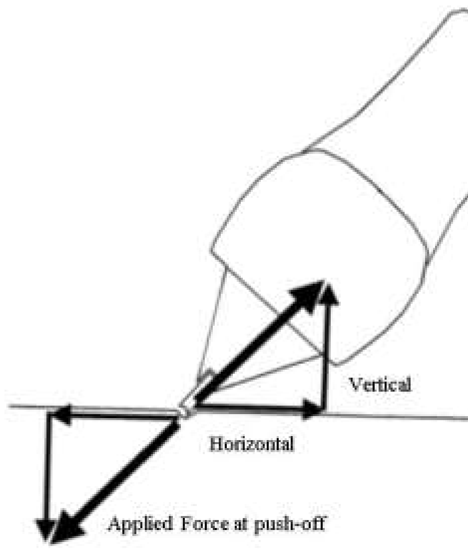

Figure 8: Skate boot angle at push off to maximize grip by the inside edge of the skate blade (Adapted from Pearsall et. al, 2007).

While there have been changes to the skate boot since its inception, a large portion of the changes have been due to necessity, and thus arose mostly through trial and error (Pearsall et. al, 2007). While these designs may serve the function they were made for, little research has gone into evaluating all these design changes, including boot stiffness. While the high cut of a skate boot arose out of the need to provide support in lateral movements, it was found to limit plantarflexion and dorsiflexion movements (Pearsall et. al, 2000). The same researchers conducted a pilot study with one subject by modifiying an aspect of the skate boot (removing the tendon guard) and found an increase in dorsi/plantarflexion but a reduction in inversion/eversion. It is evident that more research needs to be done on boot design and its interactions with the joints of the foot to help further refine skate designs so that they are maximally functional without hindering ranges of motion.

These lower limb joint motions are determined in large part by the mechanical properties of the skate boot, such as varied regional stiffness from the foot plate and design characteristics of the toe box, mid foot quarter panels, foot bed, insoles, tongue, eyelet and lacing configuration as well as the upper boot collar. Changes in one or more of these boot components could affect a player's ability and stability during various skating manoeuvres, thus affecting skating performance. For example, if the ankle lacks adequate medial and lateral support from the boot, or conversely if the boot overly restrains foot and ankle movement, the skater's ability to perform specific movements will be hindered, thereby impairing skating performance.

The goal of skate boot design is to optimize regional component stiffness to permit sufficient foot and ankle movement for balance, control and power generation while prohibiting excess laxity in movement that could lead to joint instability. Conversely, excessive immobilization of the foot and ankle could lead to compromised muscle torque and power output. These aspects of boot construction are also particularly important to study because of the time spent by skaters performing various ankle joint manipulations within the skate boot. Moreover hockey skaters were also found to have significantly greater ankle proprioceptive abilities in the inversion/eversion axis when compared to runners or sedentary individuals as well as in the plantar/dorsi flexion axis when compared to the previous two groups and ballet dancers (Li, Xu, &Hoshizaki, 2009).

1.5 Biodex Dynamometers

The Biodex System 4 Pro (Biodex System 4, Shirley, NY, USA) system and its previous versions of software and hardware are isokinetic dynamometers that are traditionally used as rehabilitation machines for the vast amounts of customization and attachments for joints. Before isokinetic dynamometers were developed, cable tensiometers were used to test the muscle response. However, since such machines were static, it was not possible to elucidate the dynamic qualities of muscular contraction. Force, work and power are not easily measured in dynamic exercise because the lever arm of the muscle continually shifts as the joint angle is modulated. Since isokinetic dynamometers provide data about the muscle load and velocity throughout the range of motion, their use in rehabilitation and conditioning has been popular as of late.

The isokinetic system needs to, by definition, hold the limb movement to the same velocity regardless of the magnitude of force exerted by the muscular components of the joint. As a result, the dynamometer would have to accomplish this by applying an external force to the joint. An electro-mechanical device in the dynamometer controls the velocity of movement by allowing the machine to absorb any extra force applied by the muscle and resists in return, by the same amount of force applied. This aspect of the dynamometer is thus similar to resistance training. However, unlike resistance training, there is no potential energy stored, as is required to slowly lower a weight that is lifted. The mechanisms behind this type of dynamometer either contain a servomotor (Biodex) or a hydraulic system to control the velocity. When a limb is placed into its attachment on the machine, its maximum range of motion is calculated before the trial, in degrees, by the experimenter. The range of motion acquired for the joint becomes the limit for the Biodex machine. The joint will not be allowed to break this limit and thus establishes a safe range of motion that can be customized to individual patients. Principles of Isokinetic exercise dictates that more torque/force can be applied with slower movement speed because this allows for greater time to recruit additional motor units.

The reliability and validity of the Biodex system has been verified in clinical and physical therapy environments (Drouin, Valovich-McLeod, Shultz, Gansneder & Perrin, 2004). Mechanically valid instrument is important to ensure that any change seen in muscle function is actually due to the musculature (or skates) instead of inconsistencies in the instrumentation, especially in clinical environments and for the purposes of this study. Drouin et al. (2004) set out to investigate the instrumentation and output of the Biodex Dynamometer by using torque, position and velocity as dependent variable. In addition to the values for the variables provided by the software, external measures for each were also taken. Position was measured by a hand held inclinometer, torque was measured by hanging calibrated weights off of the lever arm and multiplying this force by the moment arm. Velocity was measured by hanging a 4.55 kg hanging weight from the lever arm with the software set in concentric isokinetic mode. The study demonstrated that the Biodex System 3 isokinetic dynamometer was mechanically reliable and valid for the measurement of angular position, isometric torque, and slow to moderately high velocities (<300 deg/s). There was a 3%, 1% and 4% difference between calculated and observed position, torque and velocity, respectively (Drouin et. al, 2004). The safety that the Biodex machine provides by way of isokinetic exercise is exemplified by its use in rehabilitation of injured athletes and the elderly for reasons of range of motion limits mentioned earlier. In addition to its use with elderly populations, Hartmann et. al (2008) established the reliability of the Biodex system with these older subjects. The subjects were older in age because isokinetic testing protocols are not well suited for the elderly and the affects of learning the isokinetic motor task should be accounted for in test protocols. The exercises were maintained in the following order: concentric knee contractions at 60 deg/s followed by concentric knee contractions at 120 deg/s and concentric ankle contractions at 60 deg/s. There was a familiarization session followed by two test sessions that were separated by five to ten days. The highest peak torque, average peak torque and average power were the dependent variables in the statistical analysis. Even with a potentially more inconsistent group of subjects, the authors were able to show Interclass Correlation Coefficients (ICC) of ‘very good’ reliabilities for knee extension and flexion at 60 deg/s and 120 deg/s and ankle dorsiflexion at 60 deg/s with ‘good’ level for ankle plantar flexion at 60 deg/s (Hartmann, Knols, Murer, & de Bruin, 2008).

A dynamometer is a mechanical system designed to measure angular torque and velocity applied by a subject. Net torque within the system is that provided by the dynamometer on the subject, by gravity on attachments, and that provided by the subject on the dynamometer attachment. If all these forces are balanced, the dynamometer arm is stationary or going through constant angular velocity. Any non-zero net torque will result in lever arm rotational acceleration, which will make it possible to measure the isolated torque applied onto the dynamometer.

In the past, problems had arisen in controlling angular velocity and accounting for gravitational torques (Gransberg and Knutsson, 1983). This led to the development of new devices incorporating the adjustments for such issues. One of these devices is the Biodex Dynamometer (Biodex Corporation, Shirley, NY, USA).

A gearbox controls the velocity of the arm on the Biodex machine to initiate any movement. To maintain constant velocity, as set by the user, the velocity of the lever arm is monitored by a feedback mechanism comparing it to the set voltage. If the velocity exceeds this value, a resistive torque is applied to the axle (Taylor, Sanders, Howick, & Stanley, 1991).

Biodex can allow for a cushioning feature within the dynamometer machine that allows for softer impact at the ends of the range of motion. The higher the value of the cushion, the earlier the deceleration is within these ranges. The regulation of this feature is controlled from within the Biodex Advantage Software, by the experimenter. As an example, if the cushioning value is set to one, at 180 deg/s, the dynamometer will begin decelerating at seven degrees before the end stop. On the other hand, if the cushioning value is set to the max of 9, the dynamometer will begin decelerating at 45 degrees before the end stop (Taylor et. al, 1991).

In addition to the condition where the subject applies a torque on the lever arm, The Biodex System can initiate and sustain movement through a predefined range of motion, with no involvement of the subject at all. The Biodex Advantage Software controls this feature when the Passive mode is selected.

While such a mode may have therapeutic benefits for injured patients, it can also be utilized to quantify forces resisting the movements at the extremes of predefined ranges of motion, such as a skate boot or shoe.

1.6 Synthetic Ice Surface

The most common medium of skating in hockey has typically been frozen ponds, lakes and rinks that allow for an ice surface to skate on. However, minor ice surface imperfections are easily repaired and buffed over in a skating rink, which explains why they are a common skating surface (Pearsall et al., 2000). The ice surface facilitates easy gliding with a skate boot by creating a thin film of water between the surface and the skate blade. How this film of water forms is a subject of a two-theory debate; one states that it forms due to pressure of the blade on the ice surface while the other states that it is due to the surface friction generating heat and melting a thin layer of ice (de Koning et al., 1992). The thin film of water forms a type of lubricant between the two surfaces, drastically reducing the coefficient of friction. This coefficient of friction was found to be between 0.003 and 0.007 during straight speed skating.

For biomechanical analysis, in-lab equipment has been developed like skating treadmills and synthetic skating surfaces to closely replicate an ice surface to skate on. A skating treadmill has been the focus of some research as Upjohn et al. (2008) sought to find biomechanical differences between low and high caliber players as they skated on a treadmill with 4 cameras capturing the skating motion. The study found that high calibre players had greater hip flexion, knee extension and ankle plantar flexion at the push off when compared to lower calibre players. While the skating treadmill did provide the convenience of allowing video recording in a stationary lab setting, Upjohn et. al (2008) noted that some of the taller players had to restrict their stride width due to the limitations of the width of the treadmill itself. Moreover, only forward skating analysis is possible on a skating treadmill at constant velocity, as velocity is dictated by the treadmill and not the skater.

The synthetic skating surface is assembled from interconnected slabs of polyethylene plastic and, in this case, a thin film of silicone acts as the lubricant between the two surfaces. While there are multiple types of synthetic ice surfaces, little research has been done comparing the kinematics of skating on synthetic ice surfaces versus traditional ice surfaces. A recent study compared the kinetics and kinematics of skating on synthetic and regular ice surfaces over 13 meters. The authors found no statistical differences for both surfaces, including stride pattern, stride rates and total force production. While most of the kinematic parameters of ankle plantar/dorsi-flexion and knee flexion/extension were similar across the two surfaces, peak knee extension values were higher on the synthetic surface. However, for the purposes of providing a similar skating pattern for analysis in future studies, the synthetic surface was shown to be an adequate replacement (Stidwill et. al, 2010).

1.7 Kinematics

Kinematics deals with the two and three-dimensional analysis of joint movements. This often involves looking at linear and angular joint dynamics and also those of certain body segments. Kinematics does not deal with the forces that produce these movements. The study of kinematics can be applied to clinical gait analysis, running stride patterns and predictors of sports related outputs.

1.7.1 History of Kinematics

Kinematics had its objectives first rooted in the study of gait analysis. In the early 1800s, Braun and Fischer utilized Geissler tubes on limb segments and had subjects walk in total darkness while four cameras captured the light illuminated ions from the tubes on each side of the subject. Eberhardt and Inman employed a similar method by using interrupted light on a camera to capture a walking subject with small light bulbs at anatomical locations. The interruptions on the camera caused by the interruption of light created a series of white dots that could be connected to form a rudimentary figure of human gait modeling. However this process was very labour intensive and took a long time to process. During the mid 1860s, Jules Etienne Marey along with his student Gaston Carlet were the first to record the ground reaction forces of a normal human gait cycle by using pressure transducers built into the sole of the shoe. Marey went on to adapt the pressure system for horses and proved that there was a brief period of time in the horse's gait cycle where none of its hooves were in contact with the ground (Baker, 2006). At the same time, Edward Muybridge, a landscape photographer, worked on capturing a series of images of a horse trotting, including the instant none of the hooves were in contact with the ground. Inspired by this work, Marey set out to better the work of Muybridge by developing a shutter which enabled several images to be captured on a single photographic plate. This technique was then used to study pathological walking by using a moving glass plate behind the shutter to separate the images, essentially creating the first cine-camera and, by extension, an early motion capture system (Baker, 2006). Also in the 1940s, Dr. Vern Inman drilled pins into the bones of subjects and used overhead cameras to capture pin rotation and then calculate transverse plane rotations. This process was extremely painful as reported by the subjects (Sutherland, 2002).

Dr. Mary Pat Murray was one of the first scientists to use reflective tape at joint locations to provide gait data for normal men, women and subjects with pathological conditions. This is still the basis of kinematic analysis used by modern motion capture systems like Vicon (Sutherland, 2002).

1.8 Kinetics

Kinetics is the aspect of biomechanics that deals with forces that are acted on or by the muscles of the subject. Like kinematics, kinetics can also be analyzed in two or three-dimensions. If the forces are applied on the system, they can be from sources such as ground reaction forces, spring resistance, friction or wind resistance among others. On the other hand, forces applied by the system are usually initiated by muscles, tendons, and friction in the joints or some combination of these as they act through an axis of movement.

1.8.1 History of Kinetics

The first undertaking of human kinetics was again done on the subject of gait analysis. In the 1900s, Carlet and his student first studied the forces in foot and heel contact of a walking stride. They utilized air reservoirs built into the shoe to record this information and it resembled the ‘m’ shape that is observed on today’s modern force plates (Figure 9). However, at the time it was not possible to separate the force vectors into three-dimensional components. Jules Amar is credited with the advent of the world's first three-component force plate that he built with the same principle as the air reservoirs of Carlet's method, which was called "Trottoire Dynamique". Cunningham and Brown developed the mechanical force plate with four-component separation that would have clinical applications. This force plate required constant calibration because the strain gauges used in its construction were sensitive to temperature fluctuations. It was through the collaboration of scientists from three different countries that the force plate was simplified and made more easy to use along with data processing capabilities (Sutherland, 2005).

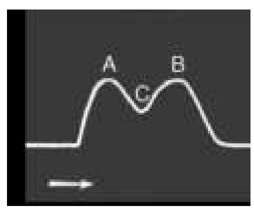

Figure 9: Typical 'm' shape of force profile produced by Carlet is similar to those seen on modern force plates. A = heel strike, B = toe off, C = transition period of weight transfer (Adapted from Sutherland, 2005).

2. Chapter 2 – Study Protocol

Biodex Dynamometer (Phase 1)

2.1 Purpose:

- Develop a methodology to mechanically quantify specific skate characteristics and design properties using a functional joint dynamometer (Biodex).This included measures of dynamic torque and range of motion in the sagittal and frontal planes. More specifically, both the passive resistance of the boot(s) (and foot ankle complex's joints and ligaments) throughout movement to the effective end points as well as the active (muscular) driven potential to create movement, torque and power will be determined.
- Use the above methodology to compare two skate models: Bauer One95 and a modified skate (figure 10). The modified skate was the same Bauer One95 skate model but fashioned with a more flexible tendon guard that allowed for greater plantar/dorsi flexion. The modified skate also had eyelets spaced closer together. The rest of the boot materials were identical to the One95 model. A standard running shoe was used as the control on the Biodex dynamometer.
- To establish and document the use of this dynamometer system for testing skate boots. Two general experimental conditions will be employed

to evaluate the design characteristics of skates using the dynamometer: active and passive. In the first instance a protocol that allows active generation of torque during dorsi-plantar flexion and inversion-eversion in the skate will be evaluated and compared to the same experimental conditions wearing a low cut running shoe. In the second instance, a protocol termed “passive” will be used to evaluate the torque required by the Biodex to induce dorsi-plantar flexion and inversion-eversion.

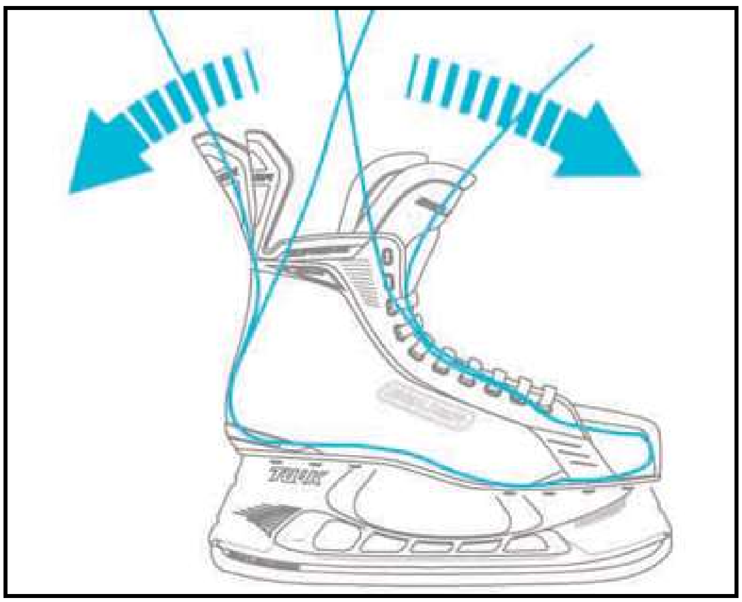

Figure 10: Modified skate with a flexible tendon guard to increase range of motion (adapted from: www.bauer.com). Figure shown is of a different skate model but the same concept is applied to the modified skate being used in this study.)

2.2 Hypotheses:

- H_1: It was hypothesized that during isokinetic - active testing, the skate boot conditions would result in lower range of motion, total work and mean peak torques than the shoe condition in the plantar/dorsi-flexion plane of movement. It was hypothesized that during isokinetic - passive testing, the skate boot conditions would result in lower range of motion but greater mean peak torques than the shoe condition in the plantar/dorsi-flexion plane of movement.

- H_2: When comparing the two skate boot models, mechanical differences in range of motion, mean peak torque and work would be observed due to the different tendon guard flexibilities. The modified skate's tendon guard was hypothesized to allow greater torque and work production because of a greater range of motion afforded by the flexible tendon guard.

2.3 Methods

2.3.1 Subject Recruitment

Male subjects between 18-26 years of age were recruited from the McGill University student community in person, as well as by email. Ten subjects were recruited for the project with five of the subjects having 'AAA' hockey playing experience and the others having recreational hockey experience. Subjects were screened before enrolment based on skate and shoe size availability. In addition, subjects who were injured and/or had a limited range of motion at the ankle joint were excluded from the study. If the exercises in this study posed a health risk to any individual, they were also excluded from the study. If at any time the subject felt discomfort, he was allowed to pause the trial.

2.3.2 Protocol

This project measured peak torques exerted and total work done about the ankle-foot complex within two skate boot types and in a running shoe as a control. Movements were performed in the sagittal plane (plantar and dorsi flexion) and the frontal plane (inversion/eversion). Each subject performed one trial per foot condition, as outlined below, with a rest period of one minute between trials to avoid muscular fatigue. In order to fit the skate boots on the foot plate of the Biodex system, the blade holder and skate blade were removed from the skate boot.

The two modes of the Biodex system used in this project were the “isokinetic” and “passive” modes, which provide different methods of acquiring data. In the isokinetic mode, the purpose was to simulate free movement of the ankle of a push-off during skating. The speed for the movement was selected at 60 degrees per second, as this was the value that allowed maximum torque production in pilot trials. This corroborates findings with Hartman et al. (2008) who found that peak torque had a negative reciprocal relationship with velocity. In the passive mode, the Biodex dynamometer moved the ankle within the participant’s safe range of motion in both planes, determined prior to testing, with no active involvement from the participant. With a predefined torque of 60 N·m and a velocity of 60 deg/s programmed into the dynamometer software, the output from this condition was the required torque to overcome resistance from shoe or skate boot characteristics restraining movement throughout the range of motion. The foot condition and Biodex exercise mode were randomized in a tier-wise fashion using MATLAB software. For example, if the first level of randomization results in the Bauer One95 foot condition, the next level of the One95 foot condition was randomized; Plantar/Dorsi-flexion (PD) or Inversion/Eversion (IE). After the second level was randomized, the next level was randomized (Active mode or Passive mode). However, subsequent foot conditions were randomized within the same tier of IE or PD and Active or Passive. This allows a more efficient randomization procedure since it takes approximately five minutes just to change the set up from PD to IE.

2.3.3 Procedures

The subject was seated and his ankle strapped to the ankle plate of the Biodex Machine, as shown in Figure 6. The subject was instructed to start upon a visual and audible cue from the monitor and the researcher. The subject was also given an emergency stop button in case he felt any discomfort during the trials. During the isokinetic trials, the subject was asked to refrain from moving any part of his body other than the ankle joint, as this could alter the results between subjects. In addition, the handles on the sides of the chair were prohibited from use to prevent its use for leverage. See Appendix A for a list of the specific set up of the dynamometer that this study employed for both the isokinetic mode and the passive mode. The angle at the knee was measured and recorded along with the Biodex seat configuration.

The subject was not allowed to view the testing monitor as it may influence his force output and cause inconsistencies between trials. In addition, the knee angle, backrest of the seat angle, height of T-bar and height of chair seat was recorded for comparison and standardization purposes. Positive values for all variables occurred during the “away” segment of the repetition and negative values occurred during the “toward” segment of the repetition. With each individual trial taking approximately ninety seconds to two minutes to complete, there were 12 total combinations of trials. Factoring rest intervals and set up time between the plantar/dorsi-flexion and inversion/eversion conditions, each subject required about an hour to complete all the trials.

2.3.4 Anthropometric Measures

Anthropometric measures of the lower limb of subjects being tested were recorded, including limb length from the hip to the lateral epicondyle, muscle girth at the greatest diameter at the thigh and lower leg around the calf. In addition, the weight and height of the subjects were recorded. Table 1 lists the mean values collected for these anthropometric measures.

Table 1: Mean anthropometric measures

Mass (kg)	85.8 kg ± 4.4 kg	
Height (cm)	177.9 cm ±- 5.1 cm	
	Left Leg	**Right Leg**
Leg Length (mm)	927.3 mm ± 25.3 mm	933.3 mm ± 25.2 mm
Knee Width (mm)	98.4 ± 4.6 mm	100.3 mm ± 6.7 mm
Ankle Width (mm)	70.0 mm ± 8.5 mm	69.0 mm ± 6.6 mm
Thigh Circumference (mm)	533.3 mm ± 20.8 mm	528.4 ± 12.6 mm
Shank Circumference (mm)	381.0 mm ± 18.5 mm	377.7 ± 13.7 mm

2.3.5 Research Design

The independent variables were foot condition, movement plane (frontal and sagittal) and exercise modes of the research design of the present study. One trial of five repetitions per subject was run for every test combination. Thus, each subject performed twelve trials in total (Table 2). A multiple analysis of variance (MANOVA) was employed in a block-randomized fashion. The confidence interval was set at 95%, with an alpha value of 0.05.

Table 2: Variables to be investigated

<table>
<tr><th>Independent Variables</th><th colspan="2">Dependent Variables</th></tr>
<tr><td rowspan="3">Foot Condition (Skate Boot or Shoe)</td><td rowspan="3">Inversion/EversionFrontal Plane</td><td>ROM (Deg)</td></tr>
<tr><td>Torque (N·m)</td></tr>
<tr><td>Work – Isokinetic (kJ)</td></tr>
<tr><td rowspan="3">Exercise Mode (Isokinetic/Passive)</td><td rowspan="3">Dorsi/Plantar-flexion Sagittal Plane</td><td>ROM (Deg)</td></tr>
<tr><td>Torque (N·m)</td></tr>
<tr><td>Work – Isokinetic (kJ)</td></tr>
</table>

This study employed a 3x2 factor research design with categorical Independent variables. The first factor had three foot conditions: two skate boots (One95 or modified) and shoe. The second factor had two exercise modes: isokinetic active and passive. Figure 11 below provides a graphical outline of how some of the dependent variables were extracted. Peak torque and range of motion are shown in the first plot while their relationship is shown in the second plot. The area under this plot was calculated for the work variable. In figure 11, the torque vs. Position plot is shown for just plantar flexion. The sum of the plantar and dorsi flexion work will result in total work done per foot condition.

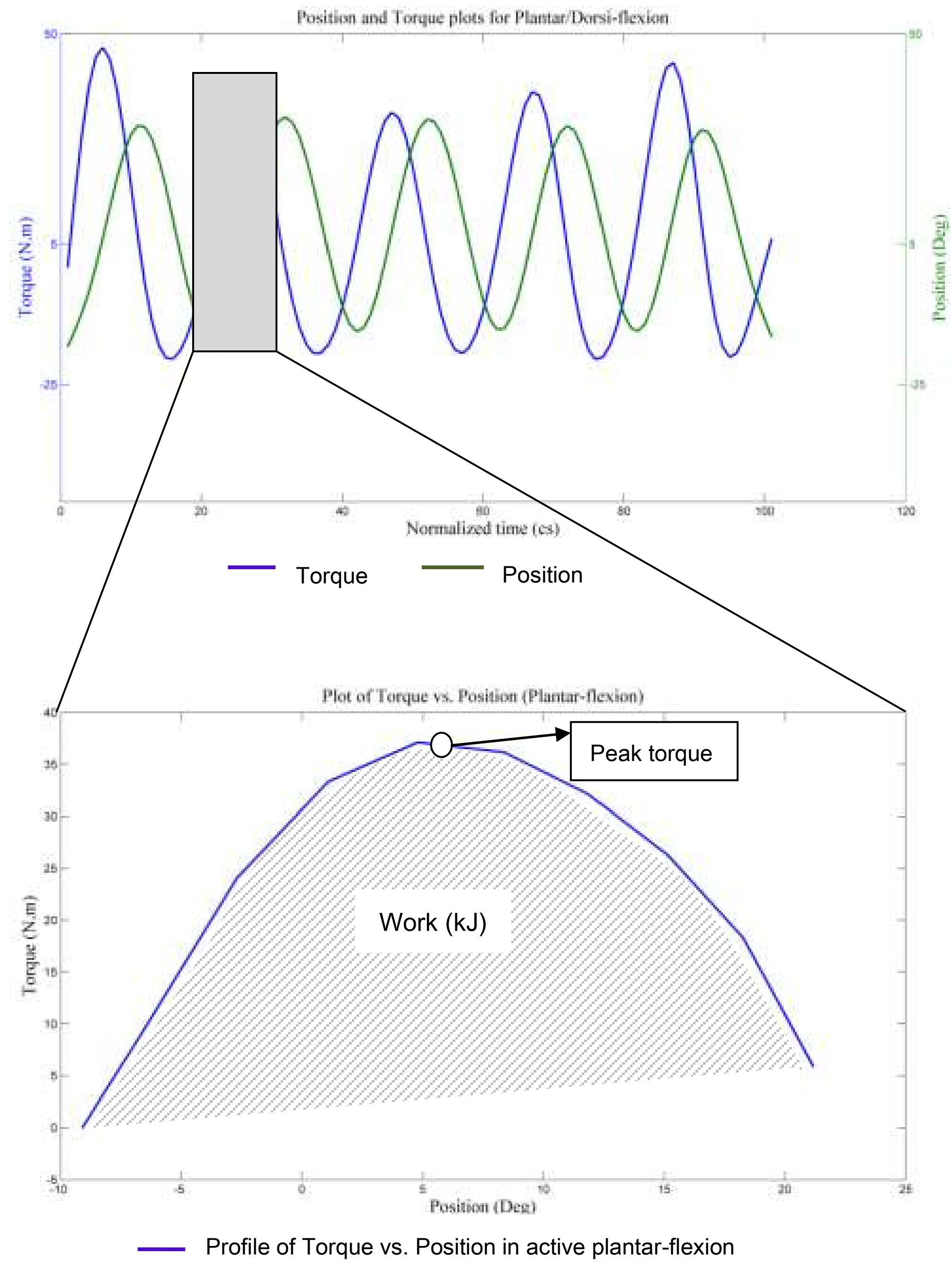

Figure 11: Graph on top providing peak torques and range of motion variables while the work variable was calculated as the area under the plot of torque versus position plot (below). The area under the curve shown is a sample for just the plantar-flexion motion.

2.4 Results

2.4.1 Isokinetic Active Mode– Plantar/Dorsi-flexion

The dynamometer was able to capture isokinetic force profiles during each footwear condition in the plantar/dorsi-flexion (PD) movement (Figure 12). Slight differences in the peak torques in both plantar and dorsi-flexion were observed during the five cycles. Greater differences were seen in PD range of motion measures between the control and the two skate boots (Figure 13). Notably, greater peak dorsi-flexion was seen for the shoe than both skates while lower peak plantar-flexion was seen for the One95 skate than either shoe or the modified skate. The 2x2 MANOVA analysis of mean maximum torque production in the dorsi-flexion motion (from plantar-flexion to dorsi-flexion) was found to be similar across all foot conditions (-25.55 N.m vs. -25.59 N.m vs -22.95 N.m, for the modified skate, One95 and shoe respectively. $p = 0.365$ for shoe-One95 comparison, $p = 0.378$ for shoe-modified skate comparison, $p = 1$ for One95 – modified skate comparison). The mean maximum torque production in the plantar-flexion motion was also similar across foot conditions (64.18 N.m vs. 62.72 N.m vs. 70.67 N.m, for the modified skate, One95 and shoe respectively, $p = 0.763$ for shoe – One95 comparison, $p = 0.834$ for shoe – modified skate comparison, $p = 0.991$ for One95 – modified skate boot comparison).

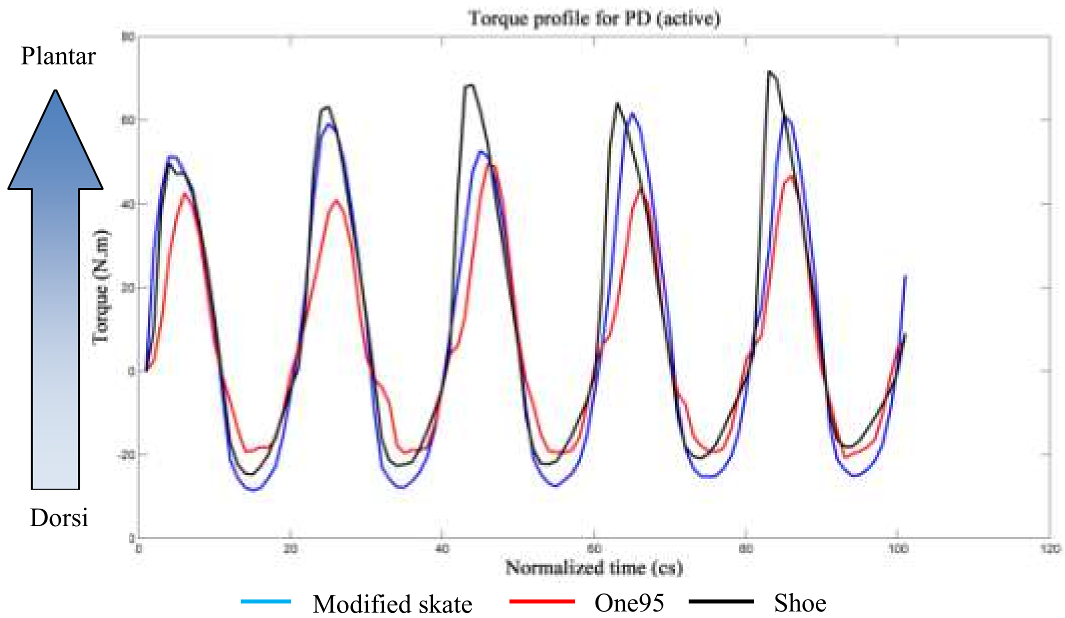

Figure 12: Sample trial of isokinetic torque profiles for the three foot conditions (blue = Modified Skate; red = One95 boot; black = shoe). Positive torque = Plantarflexion and negative torque = dorsiflexion

Comparing range of motion (max to min), it can be seen that the modified skate had a greater range of motion (ROM), similar to that of the shoe in the plantar-flexion plane (Figure 13). A 3x2 MANOVA analysis confirmed this relationship as the shoe had a significantly greater ROM followed by the modified skate and then the One95 (65.2º vs. 52.4º vs. 35.7º, $p < 0.0001$ for all combinations).

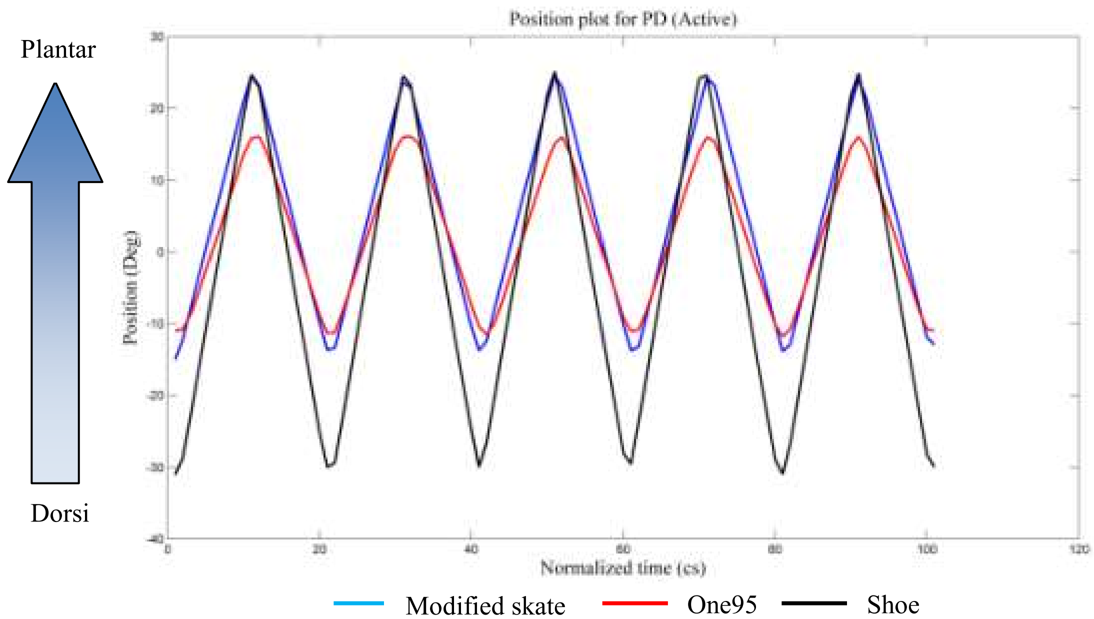

Figure 13: Sample trial of angular position (and ROM) for each footwear condition. Greatest ROM was found in the shoe, and least in the One95 skate.

The third dependent variable, total work, was calculated using MATLAB software scripts by integrating Torque (N.m) x Angular Displacement (deg) for each repetition (Table 3). Total work was not significantly different when comparing the shoe control and modified skate boot (16,113.1 J vs. 12,802.0 J, $p = 0.164$, respectively) but was significantly different when comparing the shoe control to One95 skate boot (16,113.1 J vs. 8,848.2 J, $p = 0.01$, respectively). When comparing the modified to One95 skate boot, there was no statistical difference in work done over five repetitions (12,802 J vs. 8,848.2 J, $p = 0.082$, respectively).

Table 3: Descriptive Statistics (Isokinetic – Active P/D)

Dep. Variable	Indep. Variable	Mean	Std. Deviation	N	Sig. Combinations
ROM (degrees)	A. Modified Skate	52.4	6.7	10	A-B
	B. One95	35.7	5.3	10	A-C
	C. Shoe	65.2	7.7	10	B-C
	Total	51.1	13.9	30	
Torque_Plantar (Nm)	A. Modified Skate	64.2	22.3	10	
	B. One95	62.7	27.7	10	
	C. Shoe	70.7	25.5	10	
	Total	65.9	24.6	30	
Torque_Dorsi (Nm)	A. Modified Skate	25.6	3.6	10	
	B. One95	25.6	3.4	10	
	C. Shoe	23.0	5.5	10	
	Total	24.7	4.3	30	
Total_work (kJ)	A. Modified Skate	13.0	3.5	10	B-C
	B. One95	8.9	3.5	10	
	C. Shoe	16.0	4.6	10	
	Total	13.0	4.9	30	

2.4.2 Isokinetic Passive Mode - Plantar/Dorsi-flexion

As previously explained, in the Passive mode the dynamometer does the work to move the foot and ankle. In this mode the machine moved the both the foot and ankle as well as footwear through a pre-set range of motion such that the torque resistance represents the inherent stiffness of the boot and/or limitations in the subjects' joints. Given that the end point movement for each footwear condition varied, torque vs. position plots best demonstrate the intrinsic mechanical properties of the footwear (Figure 14).The movement of plantar to dorsi-flexion was cyclic in nature and the position data cycled through two extremes of ROM for each foot condition. In the case of the shoe, for example, the peak torque would occur toward a greater end point ROM than either of the skate boots. Comparisons between conditions were made at the position of greatest torque.

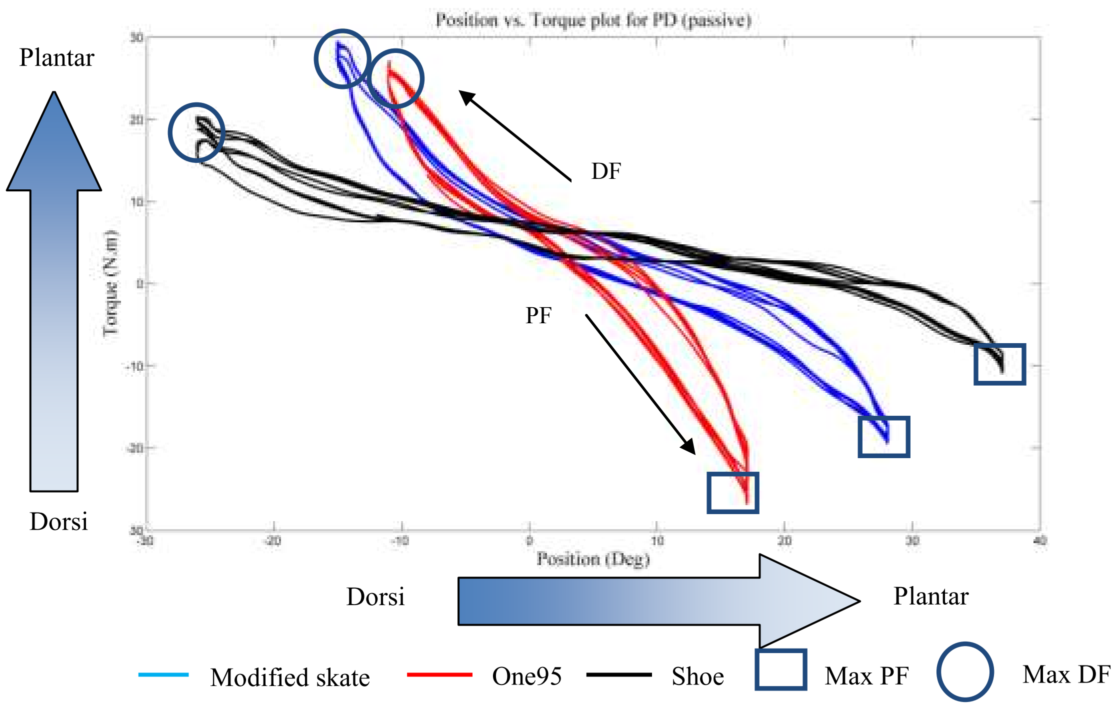

Figure 14: Passive Position vs. Torque plot for one subject to illustrate the differences in peak torque values at certain values in position. (PF = Plantar-flexion, DF = Dorsi-flexion)

Figure 14 above illustrates that the One95 skate had the highest peak torque in plantar flexion observed through the smallest ROM while the modified skate boot provided less resistant torque in plantar flexion and more ROM. Both skate boots had comparable torques and range of motion maxima at dorsi-flexion. The shoe had the greatest ROM and lowest resistant torque in both plantar and dorsi-flexion. The results of a 3x2 MANOVA confirmed this trend with significant differences in ROM between the shoe, One95 and modified skate (67.9º vs. 37.2º vs. 54.3º, $p < 0.0001$ for all conditions). The mean peak torque in the dorsi-flexion motion was significantly lower in the shoe condition than either skate conditions (20.3 N.m vs. 24.8 N.m vs. 25.8 N.m, $p = 0.003$ for shoe vs. modified skate and $p = 0.018$ for shoe vs.One95 skate). The two skate conditions were not significantly different from each other at the dorsi-flexion torque variable.

However, plantar-flexion peak torques were significantly different when comparing the shoe control and One95 boot (8.2 N.m vs 22.3 N.m, $p = 0.0$) and the modified and One95 boot (13.7 N.m vs. 22.3 N.m, $p = 0.01$). There was no significant difference between the shoe and modified boot (8.2 N.m vs. 13.7 N.m, $p = 0.049$). The general trend observed was the least resistive torque in the shoe followed by modified skate and lastly the One95 boot. Table 4 lists the descriptive statistics for the variables above while figure 15 shows the comparison of inherent resistive torque between the foot conditions for dorsi and plantar-flexion.

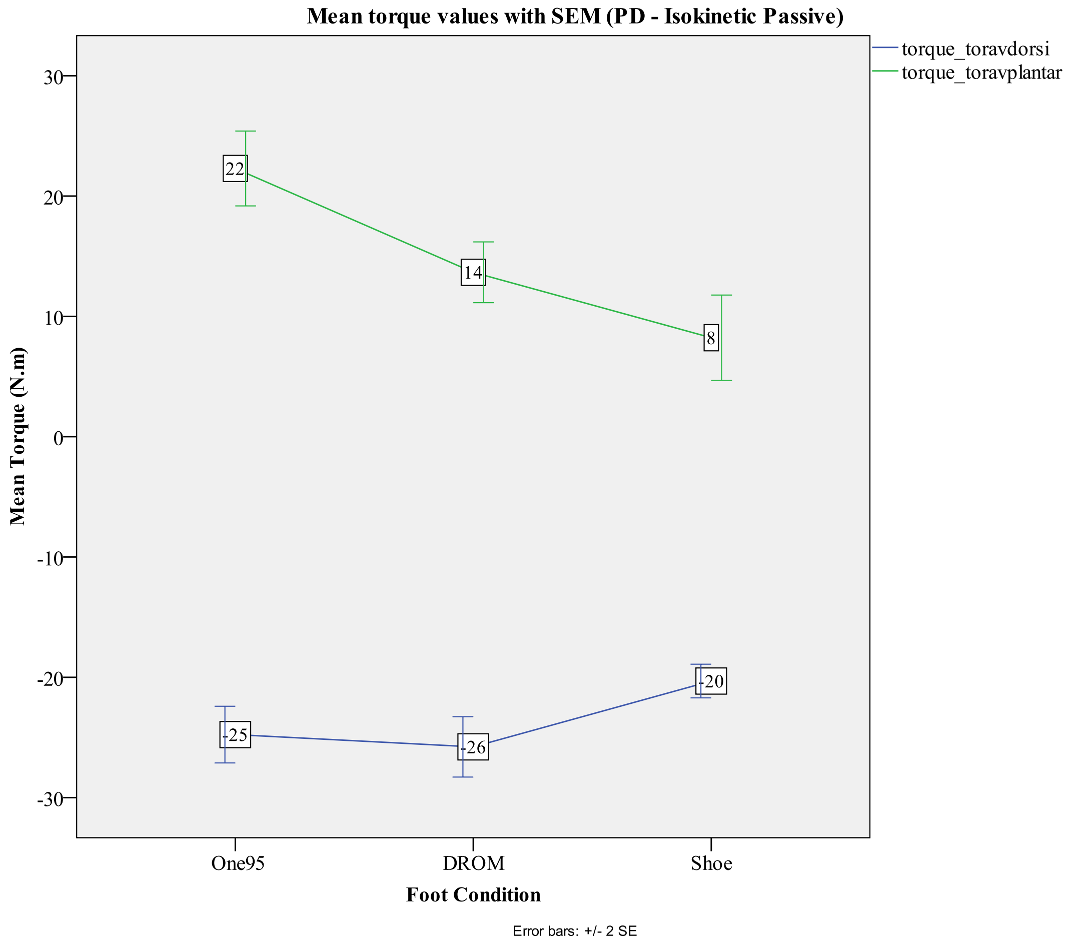

Figure 15: Mean torque values for PD (Isokinetic Active)

Table 4: Descriptive Statistics (Isokinetic Passive P/D)

Dep. Variables	Indep. Variables	Mean	Std. Deviation	N	Sig. Combinations
ROM (degrees)	A. Modified Skate	54.2	6.5	10	A-B
	B. One95	37.2	5.8	10	A-C
	C. Shoe	67.9	7.3	10	B-C
	Total	53.1	14.2	30	
Torque_Dorsi (Nm)	A. Modified Skate	25.8	4.0	10	A-B
	B. One95	24.8	3.7	10	A-C
	C. Shoe	20.3	2.2	10	
	Total	23.6	4.1	30	

Torque_Plantar (Nm)	A. Modified Skate	13.7	4.0	10	A-B
	B. One95	22.2	4.9	10	B-C
	C. Shoe	8.2	5.6	10	
	Total	14.7	7.6	30	

2.4.3 Isokinetic Active Mode – Inversion/Eversion

When comparing the maximum and minimum torques observed in the inversion/eversion (IE) movement, minimal differences were observed between the foot conditions. Graphical comparisons with the shoe control demonstrate this (Figure 16). The results of a 3x2 MANOVA confirmed that no significant peak torque differences existed.

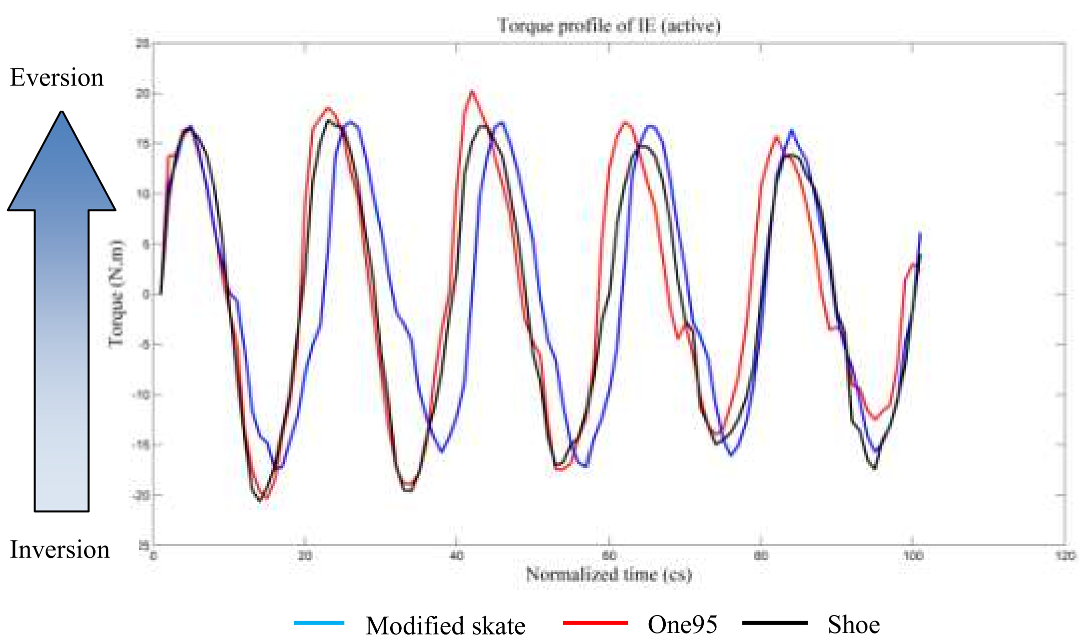

Figure 16: Sample trial of Torque vs time for all the footwear conditions. Note no large visual differences in torque were observed between conditions.

Comparing the ROM data from position versus time, it was evident that the shoe control provides significantly larger ROM in this plane than the two skate models. There was minimal difference between the skate models themselves (Figure 17). The MANOVA analysis showed significant results in range of motion for the shoe compared to the One95 and modified skate (83.7º vs. 41.0º vs. 42.1º, $p < 0.0001$ for shoe-One95 and shoe-modified skate boot comparison). There was no significant difference in range of motion between the One95 and modified skate.

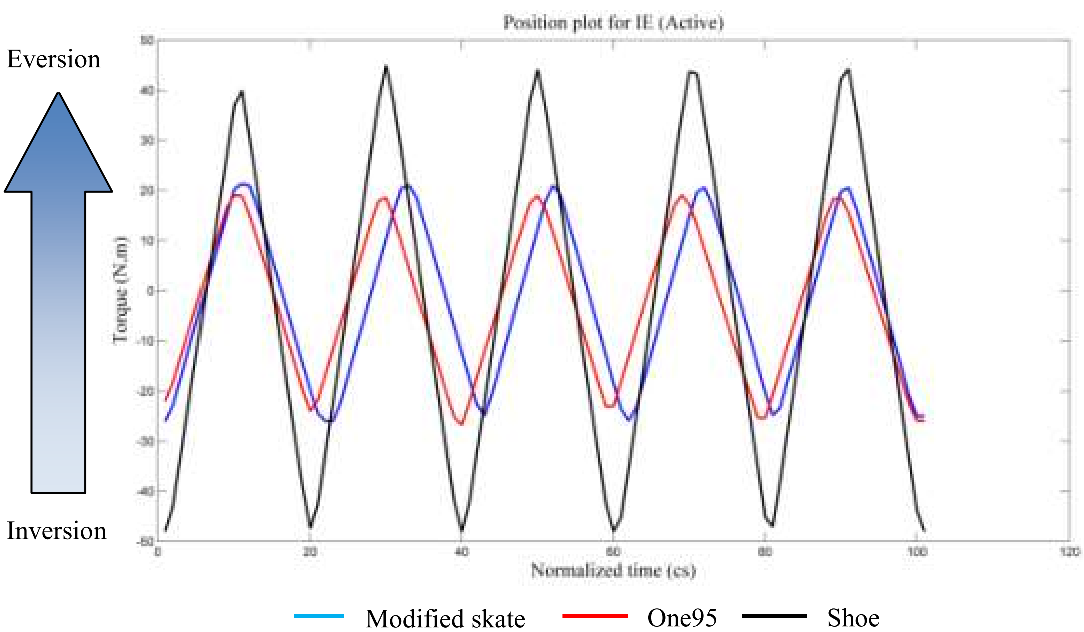

Figure 17: Sample trial of Position vs time depicts a clear difference in range of motion between the two skates and shoe control. Minimal differences between skate models were observed.

When comparing the total work done over five repetitions, the shoe had statistically higher work values over both skate conditions (11,355.3 J vs. 5753.6 J vs. 4470.3 J, $p < 0.0001$ for shoe vs. modified skate and shoe vs. One95).

There was no difference in work values for the two skate conditions. Table 5 lists the descriptive statistics for the above variables.

Table 5: Descriptive Statistics (Isokinetic Active I/E)

Indep. variables	Dep. variables	Mean	Std. Deviation	N	Sig. Combinations
torque_ROM (N.m)	A. Modified Skate	42.1	8.1	10	A-C
	B. One95	41.0	10.5	10	B-C
	C. Shoe	83.7	16.4	10	
	Total	55.6	23.4	30	
torque_tormax (N.m)	A. Modified Skate	19.8	5.3	10	
	B. One95	18.5	4.8	10	
	C. Shoe	18.9	2.3	10	
	Total	19.1	4.2	30	
torque_tormin (N.m)	A. Modified Skate	24.1	6.6	10	
	B. One95	21.7	6.3	10	
	C. Shoe	28.2	8.1	10	
	Total	24.7	7.3	30	
total_work (kJ)	A. Modified Skate	5.8	2.6	10	A-C
	B. One95	4.5	1.5	10	B-C
	C. Shoe	11.4	3.2	10	
	Total	7.2	3.9	30	

2.4.4 Isokinetic Passive Mode – Inversion/Eversion

A similar position vs. torque plot as the one in the passive mode for plantar/dorsi-flexion compared the inversion/eversion plane across foot conditions. Unlike the plantar/dorsi-flexion plane, there were no discernable differences in either inversion or eversion mean peak torques for the two skate conditions. However, large differences were seen for the shoe condition (Figure 18).

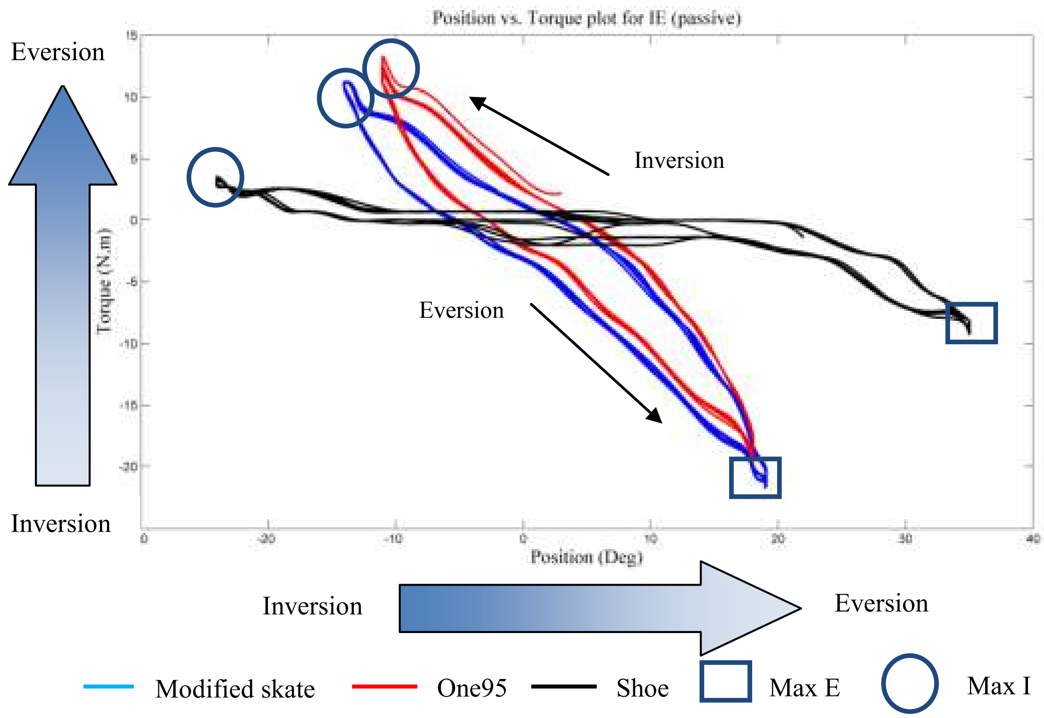

Figure 18: Sample trial of passive Position vs. Torque comparing the foot conditions in the IE plane. Minimal differences between skate conditions but large differences between shoe and two skate models observed. (E = Eversion, I = Inversion)

A 3x2 MANOVA showed statistically greater range of motion for the shoe control over the two skate models (83.7º – Shoe; 41.5º – One95; 45.5º – DROM, $p <$ 0.0001 for both comparisons of skate boots to shoe). However, there were no significant differences between the two skate models.

Mean minimum peak torque (Inversion) was significantly different for the shoe compared to the two skate models (5.7 N.m vs. 12.1 N.m – One95 vs. 11.4 N.m – Modified Skate, $p <$ 0.0001 for both comparisons of skate boots to shoe) but no differences existed between the two skate models. Mean maximum peak torque

(Eversion) was also only significantly different for the shoe compared to the two skate models (9.0 N.m vs. 17.0 N.m – One95 vs. 17.4 N.m – Modified Skate, $p < 0.0001$ for both comparisons of skate boots to shoe) and not between the two skate models.

2.4.5 Passive and Active mode (P/D)

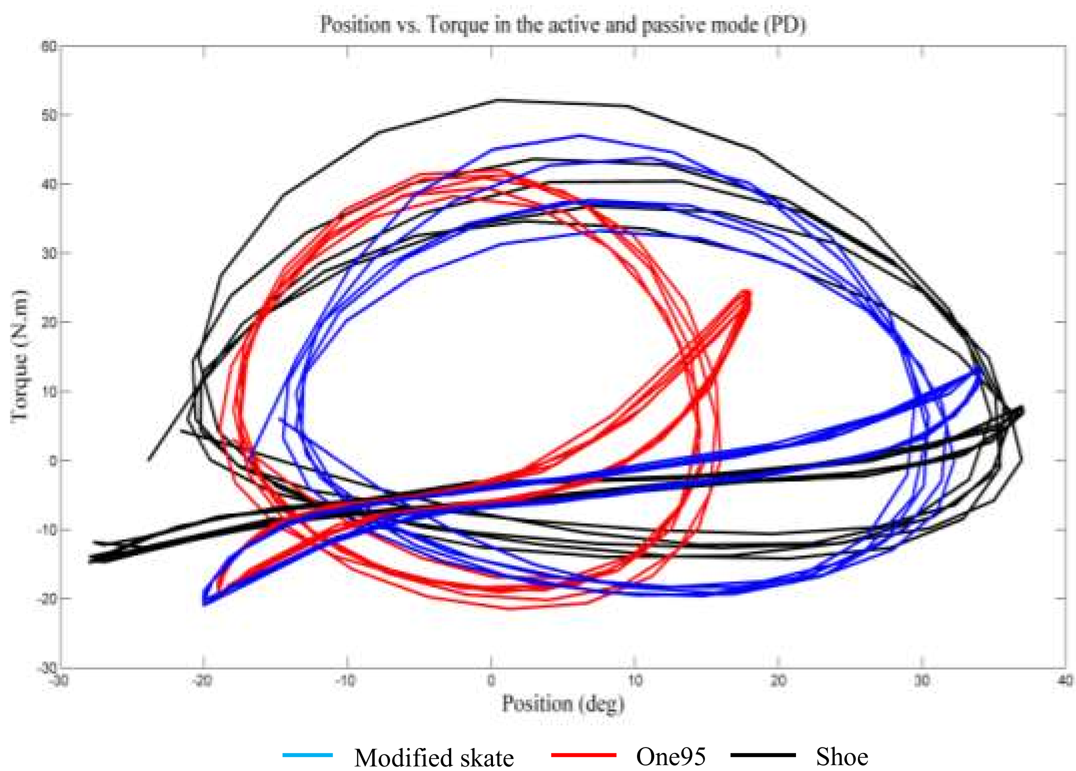

Figure 19: Position vs. Torque plot comparing the active and passive modes of movement in the plantar/dorsi-flexion plane for one subject. The spherical shapes are plots for the active mode and the narrower 'S' shaped plots are for the passive mode.

Figure 19 displays the data from passive and active modes for the plantar/dorsi-flexion plane. The circles represent the active mode for each foot condition while the 'S' shaped curves represent the position vs. Torque profiles for the passive mode. It can be seen that the intersection of the two plots for the One95 foot condition occurs at a higher torque value and lower position value than either the modified skate or shoe conditions.

The results of study one demonstrated that ROM was not a predictor of torque and work values between the skate boots. However, since the work values were significant between the shoe and the One95 in active mode, there is a trend towards greater work production with increasing ROM.

The results of the passive mode showed that the Biodex system was able to discern different stiffness properties of the shoe and the skate boots.

3. Chapter 3 –Kinematic and Kinetic Analysis of a Push-off (Phase 2)

3.1 Purpose:

The purpose for this phase of the thesis project was to:

- Analyze the kinematics and kinetics of one stride of a skating push off using the VICON motion capture system
- Compare the above measure using the same two skate models tested in Phase 1 (no shoe control)

3.2 Hypotheses

- H_1: It was hypothesized that the modified skate would have greater ankle range of motion in the plantar-flexion plane along with greater peak force at push off, as in phase 1.
- H_2: It was hypothesized that upper joint (knee and hip) angles would be different with the modified skate boot as the ankle is allowed to move through a greater range of motion.

3.3 Protocol/Methodology

This phase of the project focused on the collection of kinetic and kinematic data from the first stride of a skating push off. Subjects stood on two force plates with one foot on each. Only the force plate under the right foot was recording data and subjects were instructed to perform a regular skating push off facing the intended direction of travel using the right foot as the push off skate on a synthetic ice surface in lab (Figure 20).

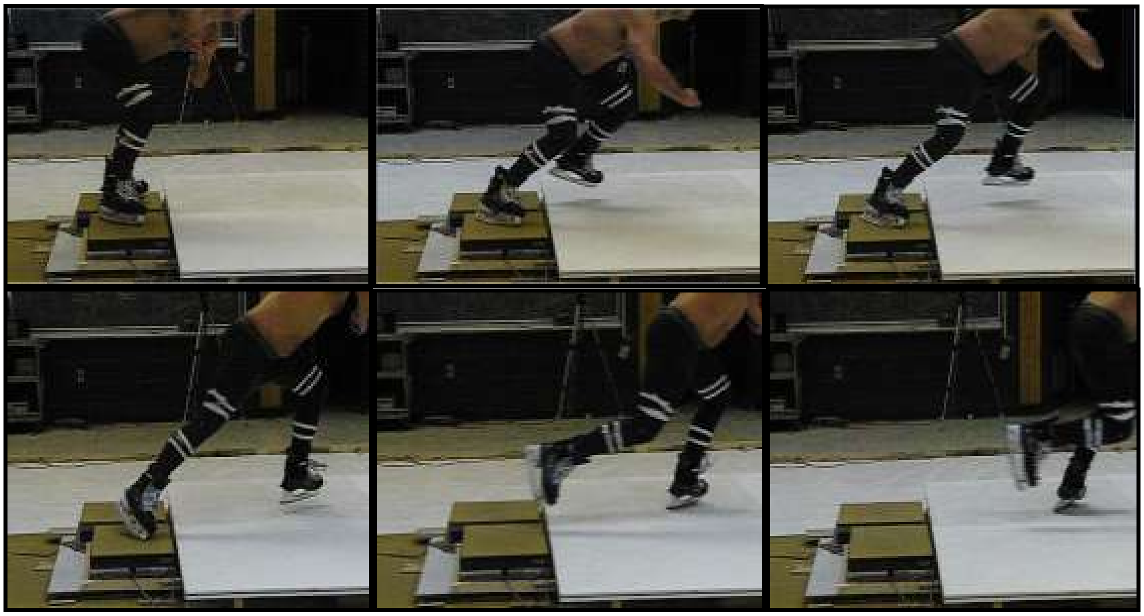

Figure 20: Six frames of the skating push off required in this phase of the study.

The surface of the ice was elevated to allow the force plates to be level with the skating surface to closer replicate a skating push off (Figure 21).

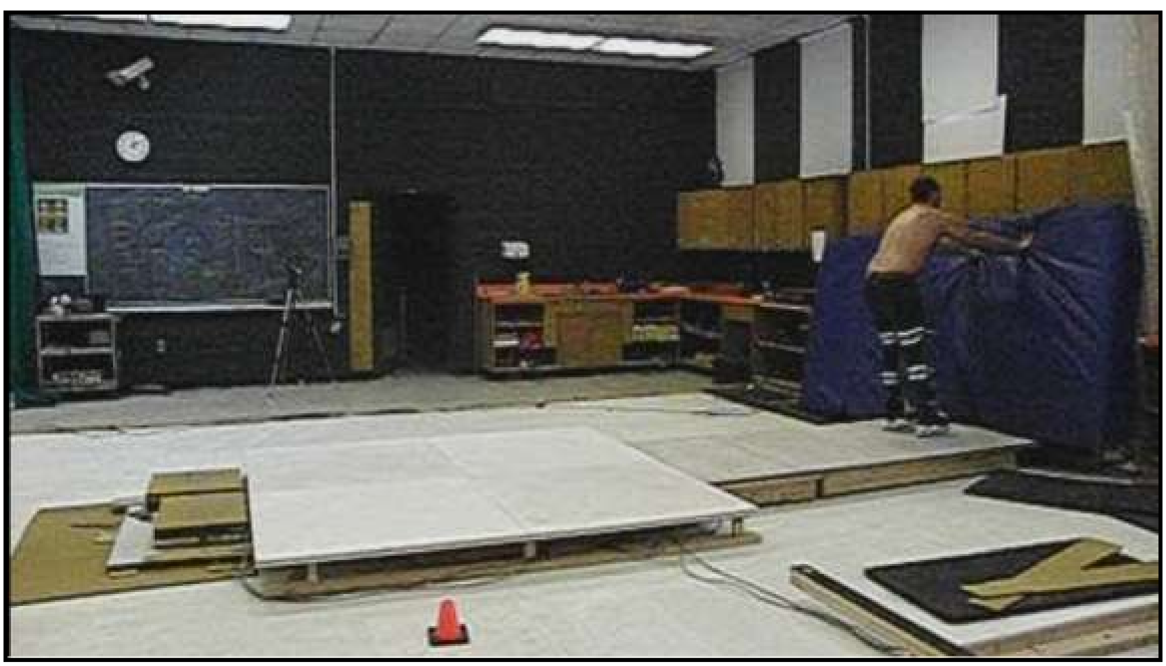

Figure 21: The elevated skating set up with only the right force plate recording data. Subjects will push off of this right force plate and stop using the crash pad at the end of the surface (blue).

Each subject was also fitted with reflective markers on the right and left anterior and posterior superior iliac spines, thigh, knees and tibia of both left and right lower limbs according to Plug-n-Gait model (Vicon™). The toe box, heel and the area around the lateral maleolus of the boot itself also had reflective markers (Figure 22). These markers were then captured using infrared emitting motion capture cameras as part of the VICON system. Data was collected from the force plate at 1000 Hz and from the VICON system at 200 Hz. All up-sampling and data combining was done using MATLAB software. The VICON data was filtered using a 4th order Butterworth filter set with a cut off of 25 Hz while the force plate data was set with a cut off of 18 Hz. Approximate time required from the participants for this phase of the project was approximately 45 minutes. This estimate includes the subject set up of anatomical marker placement, subject calibration and the testing itself.

Figure 22: Marker placement on skate (adapted from Stidwill et. al, 2010)

Prior to the start of each skate type, subjects were allowed to warm up and acclimatize to the skates using a self set duration and pattern of warm up procedures. A crash pad at the end of the skating surface allowed the skater to come to a safe stop. Five repetitions of the push off were to be completed for each skate boot (Bauer One95 and the modified skate) with approximately thirty seconds to a minute rest between repetitions.

3.3.1 Axes conventions

For each of the joint angles, a global convention is used by the VICON system to signify specific joint motions. Table 6 below summarizes these conventions.

Table 6: VICON Motion detection global sign conventions

Joint	X-Plane: Positive Values	X-Plane: Negative Values	Y-Plane: Positive Values	Y-Plane: Negative Values	Z-Plane: Positive Values	Z-Plane: Negative values
Hip	Flexion	Extension	Adduction	Abduction	Internal	External

					Rotation	Rotation
Knee	Flexion	Extension	Varus	Valgus	Internal Rotation	External Rotation
Ankle	Dorsi-flexion	Plantar-flexion	Internal Rotation	External Rotation	Inversion	Eversion

3.3.2 Subject Recruitment

This phase employed the 'AAA' level subjects from the first phase of the project (24.8 years old +/- 1.8 years, 81.7 kg weight +/- 8 kg, 177 cm height +/- 5.5 cm). Two subjects were not able to return for this phase of the study while three additional subjects were recruited from the McGill student community. Thus, this section had six subjects that participated in the skating push off analysis.

3.4 Results

3.4.1 Kinematics

Only the right leg was assigned as the push off leg for kinematic analysis. When comparing the angles of the hip, knee and ankle boot complex in the first stride of a skating push off, the profiles of both plots comparing the foot conditions followed a similar trend with their mean lines (Figure 23). This plot was normalized to hundred percent with the end point being defined as when the subject's push-off foot was lifted off of the force plate just after the first push.

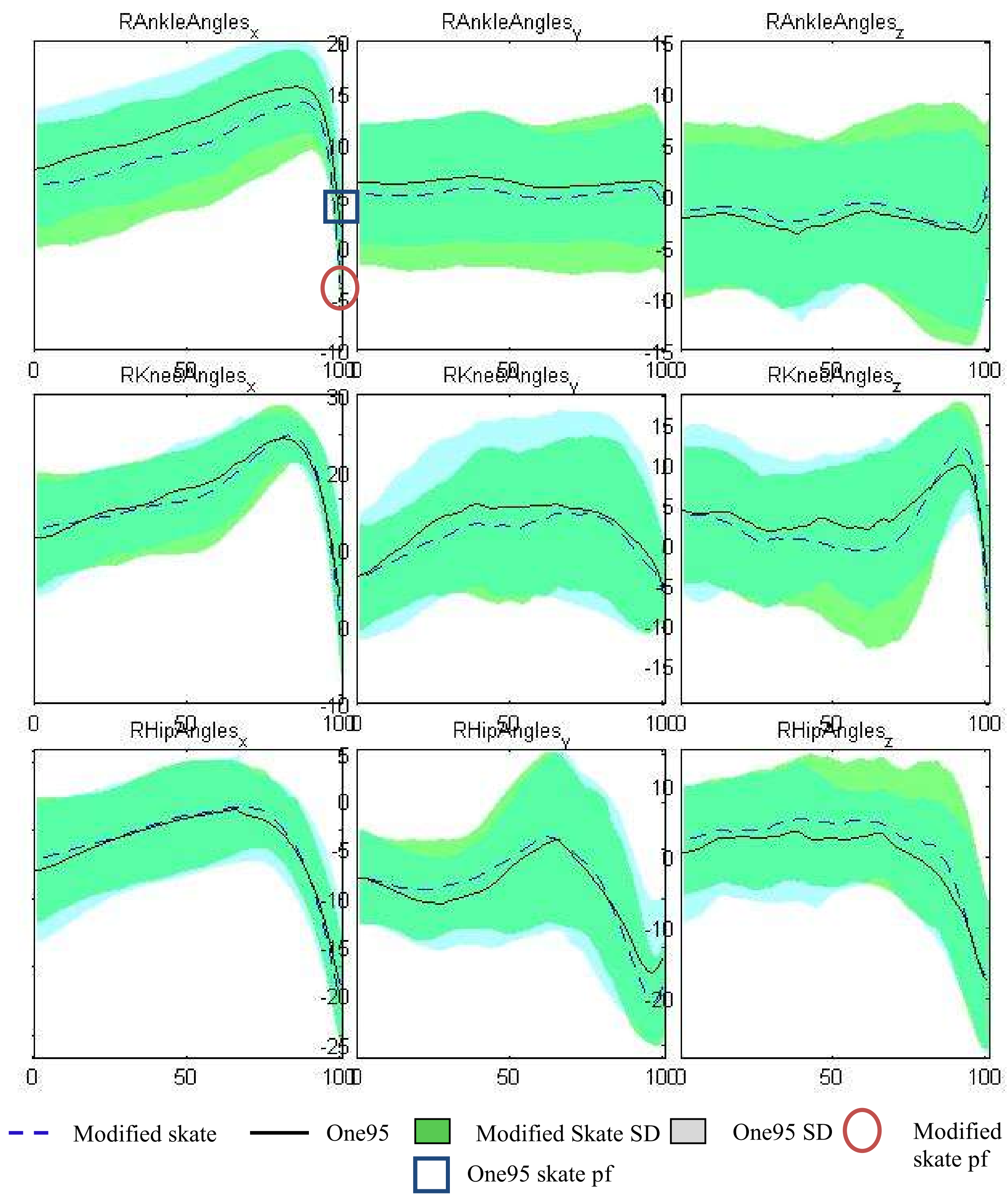

Figure 23: Group average of joint kinematic plots of the angles at the Ankle, Knee and Hip joints. Only one significant difference was found at the right ankle minimum angle in the x plane (Plantar Flexion).

A two- way MANOVA was run comparing the modified skate and the One95 skate on each joint axis angle of movement. Of all the joint planes, only the minimum angle value of the right ankle angle in the x-plane for the modified skate was significantly different from the One95 skate (-11.3º vs. -1.3º, p = 0.007) . This means that the modified skate had a significantly greater plantar flexion angle towards the end of push off.

3.4.2 Kinetics

When comparing the force plate data for the right foot push off, the mean line profiles for both the One95 and modified skate were similar (Figure 24). A two-way MANOVA was run on the dependent variables of peak force in all three x, y and z planes, showing no significant difference in peak force between the two skates.

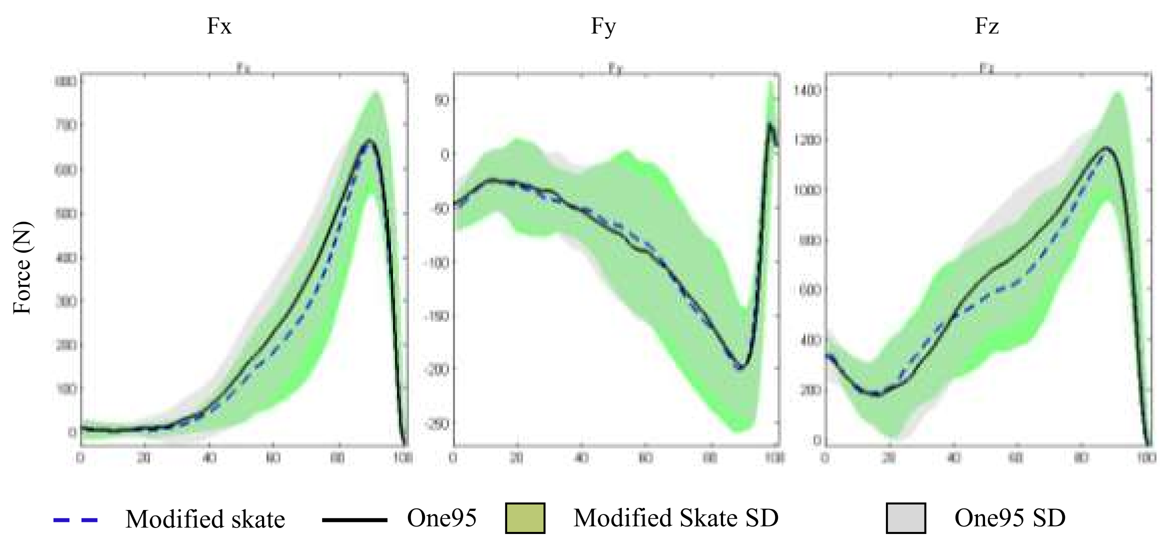

Figure 24: Mean torque profiles comparing the One95 skate boot and modified skate boot for three axes

4. Chapter 4 - Discussion

Phase 1:

The Biodex dynamometer system proved to be a sensitive instrument to differentiate mechanical outcomes under the different footwear conditions. The machine also made it possible to compare passive and active behaviours. To the author's knowledge, this is the first study of its kind to quantify the functional consequences of different skate boot constructions on foot and ankle dynamic torque capacities. Prior studies have only estimated these by either mechanical testing of the skate boots alone (Turcotte et al., 1999) or indirectly using mathematical models (Hettinga, 2009). Hence, the dynamometer testing provides an effective tool to "benchmark" the functional consequence of changes in skate boot materials, design and construction in a controlled laboratory environment and with human subjects. Further inspection of the data provides greater insight into the specific interaction, as discussed in the text.

4.1 Isokinetic active – plantar/dorsi-flexion

The results supported the first hypothesis that lower range of motion (ROM), total work and mean peak torques would occur in the skate boots than the shoe conditions. The shoe's greater range of motion was to be expected since it physically did not obstruct the ankle. However, this did not translate into differences in mean peak torques between footwear conditions. According to the torque data, the anterior and posterior leg musculature were equally capable of torque generation for all footwear conditions. Given the above combinations of ROM and torque, the rank order trend observed for total work estimates (over five repetition cycles) was greatest for the shod condition (16.1 kJ), followed by the modified boot (12.8 kJ) and least for the One95 boot (8.8 kJ). Significant differences were found only between shoe vs. One95. A study designed to measure the limb strength of professional soccer players on a dynamometer found the average torque in dorsi-flexion to be 24 N.m and 115 N.m in plantar-flexion (Fousekis et. al, 2010).

4.2 Isokinetic active – Inversion/Eversion

Similar to PD, the resulting IE plane ROMs were greater in the shoe compared to both skate boots. Unlike PD, both skate boots had similar IE ROM, indicating that upper collar and lacing construction differences between the modified and One95 boots did not change side to side foot and ankle mobility. In terms of torque measures, no statistical significances were found between footwear conditions. With regards to work done, this was greater in the shoe (11.4 kJ) than either the modified (5.7 kJ) or One95 (4.5 kJ) boots. Since the shoe allowed for a greater angular displacement with similar torques, the work done was greatest in the shoe control group. A reliability study on the dynamometer in the inversion/eversion movement reported active torque production in the inversion plane of about 24 N.m at 60˚/s and of about 18 N.m at 60˚/s in the eversion plane of movement (Aydog et. al, 2004). This project reported a mean peak inversion torque of 24.67 N.m and eversion torque of 19.07 N.m at 60˚/s.

4.3 Isokinetic passive – Plantar/Dorsi-flexion

As noted earlier, the passive mode testing involved the dynamometer moving the subject's foot and ankle through a preset range of motion without any muscular effort by the subject. It was hypothesized that the skate boots would result in less PD ROM but encounter greater "resistive" torques than with the shoe. This was supported by the findings of the study (Figure 14). The One95 encountered the highest torque resistance and least ROM. Conversely the shoe condition showed the lowest torque and greatest ROM. The modified skate behaviour fell in between the shoe and the One95 in encountered torque. The latter differences in stiffness properties may be attributed to different upper boot construction, in particular the more flexible achilles tendon guard. In turn, the subjects' perceived this lower stiffness at the back of the boot and they were thus able to move to greater plantarflexion and thus greater net ROM. Figure 14 shows a hysteresis effect observed in the torque vs. position plots in this mode. Hysteresis is defined as a system with a memory, whereby the current state is dependent on its history or a previous state (Mielke & Roubicek, 2003). As can be seen, the path taken from dorsi-flexion to plantar-flexion was different than the path taken from plantar-flexion to dorsi-flexion. The results demonstrate greater resistive torques occured when moving towards the end ROMs than when returning to neutral foot and ankle position. There was a delay in the reaction of the system (torque) to a reversal of movement (position). This held true for all foot conditions. Similar hysteresis was seen in other studies studying the passive mode on a dynamometer (Anderson et.al, 2010). The shoe also had a large mid-range ‘plateau’ (or very low stiffness) representing a region of low resistive torque by the ankle foot complex. Comparably the resistive torque free plateau was shorter in the modified skate it was practically non-existent in the One95 skate boot. Even though the peak torque production was not different, the work done under a larger range of motion should have been greater for the modified skate, as was seen for the shoe control. However, the sample variances were too large to conclude that.

4.4 Isokinetic Passive – Inversion/Eversion

Similar torque-angle profiles for the isokinetic passive mode in the inversion/eversion (IE) plane of movement were seen (figure 14) in comparison to PD. However, no statistical differences were found in IE ROM or torque between the two skate boots. The shoe had a greater ROM and lower resistive torque values than both skate conditions. The torque-angle relationships were similar for both modified skate and One95 (Figure 15). The plateau mentioned earlier was also significantly larger for the shoe control than either skate boot. These results were consistent with the isokinetic active IE testing.

4.5 Comparison between Active and Passive Modes (P/D)

The figure below outlines the basis of the comparison between the active and passive modes in plantar/dorsi-flexion. The solid and broken arrows provide the distinction between the types of torque that are outputted by the dynamometer software, depending on the mode of operation (Figure 25). The solid arrows (and text box) outline the torque outputted by the dynamometer while the broken lines are resistive torques encountered by the subject or dynamometer, depending on active or passive mode. In active mode, the outputted torque is provided by the subject and is in the direction of motion (Figure 25, solid line, quadrant: 1,1). It registers the subject's ability to push the foot plate in the intended direction of motion. In this active mode, there is also a resistive torque provided by the dynamometer to limit the velocity by which the subject can move the foot plate, as per the isokinetic guidelines (Figure 25, broken line, quadrant: 1,1). This applies in both plantar-flexion motion and dorsi-flexion motion (Figure 25, quadrant: 1,1 and 1,3). In the passive mode, the torque outputted is the resistive torque encountered by the dynamometer, and points in the opposite direction of motion (Figure 25, quadrant: 1,2 and 1,4).

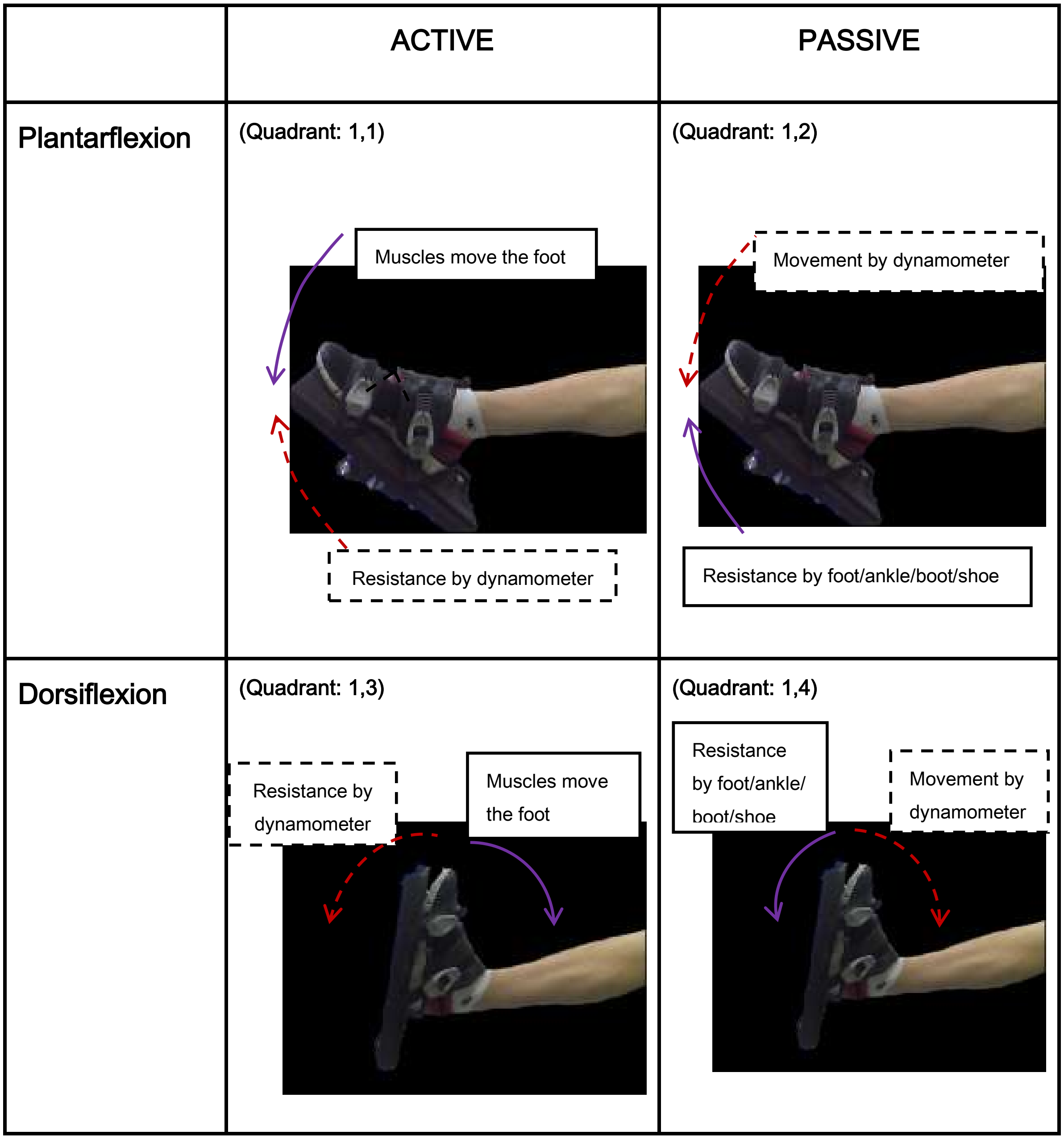

Figure 25: Comparison of ACTIVE and PASSIVE modes on the Biodex dynamometer. In the ACTIVE mode the recorded torques (solid lines) were those generated by the subject's muscles on foot (ACTION). In the PASSIVE mode the recorded torques (solid lines) were generated by the boot and foot / ankle / leg (no muscle activation; REACTION) to resist the Biodex's pedal.

Comparing the two modes for plantar/dorsi-flexion, it can be seen that the peak torques for the active mode average about the neutral position, hovering around the 0˚ mark (Figure 26).

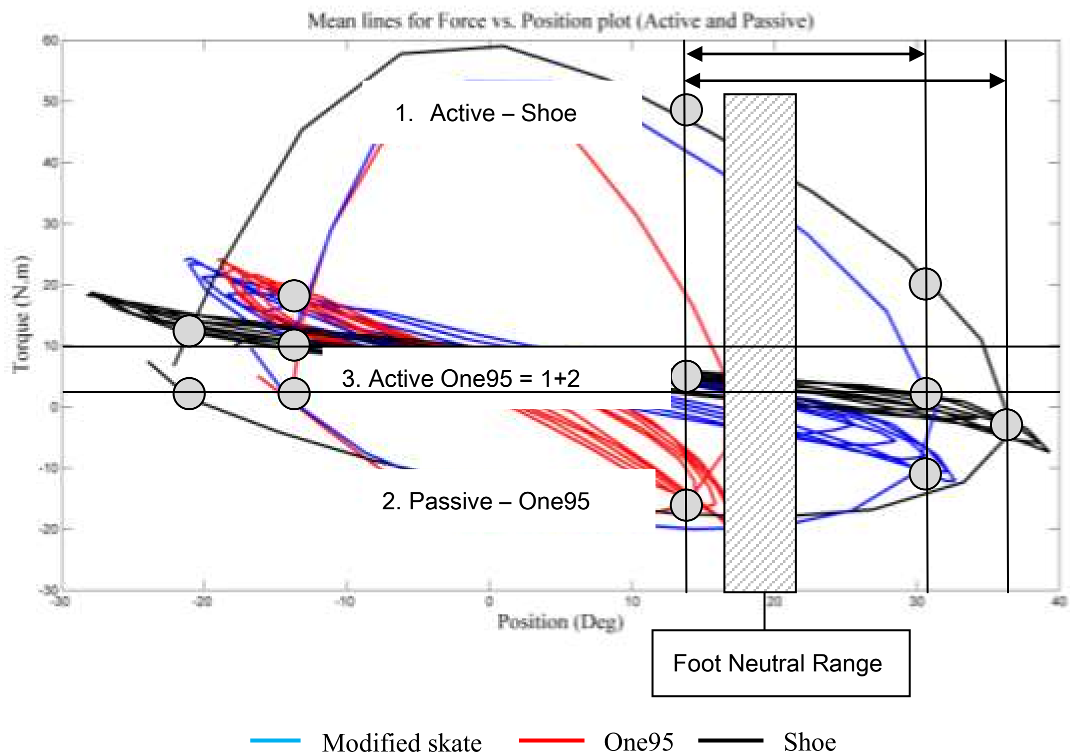

Figure 26: Mean lines of comparison of active and passive modes in plantar/dorsi-flexion plane for all foot conditions. One repetition in the active mode (circles) is shown.

In contrast, the peak (resistive) torque in the passive mode occurs at the ends of the range of motion. Consequently the passive (resistance) torque did not play a role in countering the active torque created by the muscle excitation until the late end phases of movement. However, at these extreme positions, the passive (resistive) torque in plantar flexion reduced the net active torque by up to 25% for the One95 skate boot and 17% in the modified skate. The intersection of the graphs for each respective condition can be described as the point at which there is greatest resistance to active movement. Any more movement in either direction would result in an exponential increase in resistive torques, probably perceived by the subjects as increased contact pressure, as well as discomfort or even pain. This point can be used to describe the boot stiffness characteristics. For example, from figure 26, it can be seen that for the One95 skate boot, at the intersection point of the two red plots (~12˚) the net resistive and muscle generated torques was 15 N.m. However, for the modified skate boot, the intersect was around 32˚ with a net resistive and muscle generated torques of about 8 N.m. This shows that in the plantar-flexion plane, the modified skate boot had lower maximum resistance to active movement at a greater plantar-flexion angle. Since there was no modification in the dorsi-flexion plane, the intersection of the plots occurs at about the same coordinates.

Another artefact worth mentioning in Figure 26 is the viscoelastic effects observed in the passive plots towards the end of ROM. Each successive repetition has a slightly greater ROM, resulting in a ‘fanning out’ pattern seen at the ends of the passive plot. This viscoelastic effects are a result of the deformation of the muscles, tissues, tendons and ligaments involved in the movement of the joint (Yoon & Mansour, 1982).

Phase 2:

4.6 Kinematic and Kinetic Analysis of a Skating Push-off

The first hypothesis for phase two of the study was that the modified skate would have a greater ankle range of motion in the plantar-flexion plane and a greater peak force at push–off. Although there was a significantly greater ankle plantar flexion angle with the modified skate the peak forces observed were not different. The plantar flexion end point occurred at a greater angle in the modified skate right before the subject's push off skate was lifted off of the force plate (Figure 23). Since the force production was the same for both skate conditions, this corroborates the findings from the above dynometric study. Both dynomometer and skating push off analyses showed greater foot and ankle movement in the modified skate but neither has shown a greater torque/force or work production as a result of this greater ROM. One possible reason could be that the subjects were not accustomed to the modified skate for long before they were required to perform maximal push off trials. This has been a limitation of this study because if the subjects are allowed to use the skates during their practice or hockey games, there was potential to take advantage the greater ROM to apply more prolong torque as elicited in the dynomometer.

4.7 Comparisons between phase 1 and phase 2

Comparing the mean range of motion values from the first and second phases (right ankle, x axis data from phase two), the One95 had a ROM of 35.7º while the modified skate had a significantly higher ROM of 52.4º in phase 1. Mean ROM for the One95 skate boot in phase 2 was 35.2º while the modified skate had a ROM of 41º . Comparing these sets of values, it was evident that the One95 skate boot was very similar across both phases while the modified skate had a lower mean ROM in phase two on the synthetic surface than on the Biodex dynamometer in phase one. This suggests that while both skate boots were assessed at their respective extremes of ROM, the ROM of the One95 was used to the same extent in a skating push-off. The modified skate, however, allowed for a greater theoretical ROM on the Biodex dynamometer but only a portion of that was used in a skating push-off. This could also be explained by one of the limitations of the study discussed earlier: there was no familiarization period with the modified skates.

The total plantar/dorsi-flexion torques (plantar-flexion torque + dorsi-flexion torque) found in phase one under the isokinetic-active mode averaged 88.2 N.m for the shoe, 89.73 N.m for the modified skate and 88.33 N.m for the One95 skate boot. These torques were comparable to those found at the ankle joint in a speed skating push off study (Hettinga, 2008). Hettinga had skaters pushed off with their right skate against a wooden block on a force plate onto a modified skating plastic in lab. Using inverse dynamic analysis the peak torque found at the ankle was about 100 N.m. This was then compared against a simulation created by the author, of a speed skating push off (Hettinga, 2008).

Hettinga's data from the force plate yielded average force plots for the ground reaction forces (GRF) with the vertical GRF peaking at 704 N, lateral GRF peaking at about 600 N and posterior GRF peaked at about 165 N. In comparison to this study in phase two, the vertical GRF peaked at 1180 N, lateral GRF peaked at 680 N and posterior GRF peaked at 190 N (Figure 27). The lower vertical GRF in the speed skating study can be accounted for by the fact that the authors defined the start of the push off as when the klap skate's hinge mechanism began to open. This meant that the subject was already leaning away from the force plate at the start of push off (Hettinga, 2008). Thus, there was no peak of increased vertical GRF.

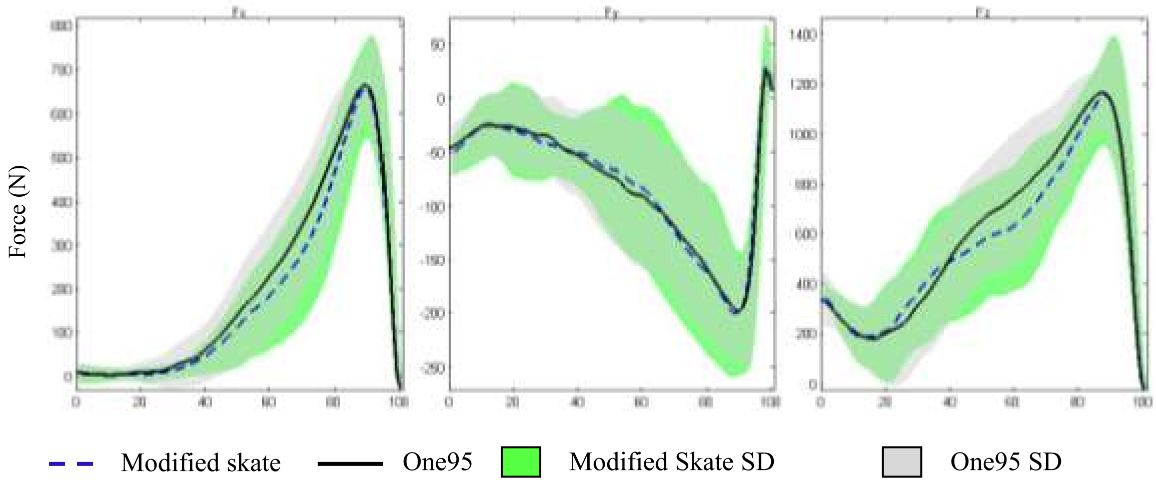

Figure 27: Mean torque profiles comparing the One95 skate boot and modified skate boot for three axes

The agility required in ice hockey skating necessitates the use of a skate to its full potential. The skate boot must provide an optimal combination of stiffness (to secure the rigid blade about more compliant and deformable the foot and ankle complex) and degrees of freedom for movement. These two properties will in turn affect both the amount of joint work possible (relevant to effective propulsion in skating locomotion) and the player's dynamic stability. As was evident from this study's first test phase, functional mechanical changes between footwear conditions demonstrated by the dynamometer did not necessarily translate into biomechanical changes during push off simulation tasks. The latter phase of testing had limitations, such as lack of subject familiarization with the modified skate and evaluation of only the first skate stride push off. Hence, further testing in conditions emulating on ice skating, as well as on ice, are needed.

5. Chapter 5 - Conclusion

The Biodex dynamometer proved to be effective in quantifying the interaction between intrinsic boot stiffness characteristics and the wearer's ability to generate movement. Further, using the two exercise modes (passive and active) functional mechanical differences footwear conditions were detected. Clear differences between the modified and One95 skates were shown in foot/ankle complex plantar/dorsiflexion mobility and torques though total work done per trial was not significantly different. Similar findings were shown in the push-off simulation analysis (phase 2): greater plantarflexion in the modified skate and equivalent ground reaction forces between skate models. Nonetheless, the short familiarization period to modified skate for the subjects may well underestimate potential long term motor behaviour adaptations leading to augmented propulsion. Support for this opinion comes from early research done on the klapskate that showed subjects did not achieve the full potential of the skates until they were allowed time to modify their skating pattern by practicing with the klapskate for an extended period of time. At the 1994 Winter Olympics, these athletes proceeded to break short and long track speed skating records (de Koning et. al, 2000; van Ingen Schenau, 1996). Thus, it would be interesting to perform studies on athletes that have had an extensive familiarization period with the modified hockey skate boot to see if any additional mechanical differences exist in such a comparison of skate boots.

6. Chapter 6 - References

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Appendix A – Software Configuration

Biodex Dynamometer Setup (Plantar/Dorsiflexion):

Table 7: Preliminary Biodex system setup (Plantar/Dorsi)

Angle	90
Tilt	0
Dynamometer Height	Variable
Foot Plate	Attached
Leg brace	Attached
Seat Height/Tilt	Variable

The following table lists parameters for the Isokinetic mode only. Table 3 lists parameters for Passive mode.

Table 8: Software set up for Plantar/Dorsiflexion in Isokinetic Mode

Exercise Mode	Isokinetic
Exercise Type	Plantar/Dorsiflexion
# of Sets	1
# of Reps	5
Exercise Velocity	500 (deg/s)
Contraction type	Concentric/Concentric

Cushion Type	1-Hard
Attachment Sensitivity	3-Ankle

Table 9: Software set up for Plantar/Dorsiflexion in Passive Mode

Exercise Mode	Passive
Exercise Type	Plantar/Dorsiflexion
# of Sets	1
# of Reps	5
Exercise Velocity	180 (deg/s)
Exercise Torque	30 N.m
Contraction type	Concentric/Concentric
Cushion Type	1-Hard
Attachment Sensitivity	3-Ankle

Biodex Dynamometer Setup (Inversion/Eversion):

Table 10: Preliminary Biodex System Setup (Inversion/Eversion)

Angle	0 deg
Tilt	50 deg
Dynamometer Height	Variable
Foot Plate	Attached

Leg brace	Attached
Seat Height/Tilt	Variable

The following table lists parameters for the Isokinetic mode only. Table 6 lists parameters for Passive mode.

Table 11: Software set up for Inversion/Eversion in Isokinetic Mode

Exercise Mode	Isokinetic
Exercise Type	Inversion/Eversion
# of Sets	1
# of Reps	5
Exercise Velocity	500 (deg/s)
Contraction type	Concentric/Concentric
Cushion Type	1-Hard
Attachment Sensitivity	3-Ankle

Table 12: Software set up for Inversion/Eversion in Passive Mode

Exercise Mode	Passive
Exercise Type	Inversion/Eversion
# of Sets	1

# of Reps	5
Exercise Velocity	180 (deg/s)
Exercise Torque	30 N.m
Contraction type	Concentric/Concentric
Cushion Type	1-Hard
Attachment Sensitivity	3-Ankle

*The software setup after this point for ankle Inversion/Eversion is the same as for Plantar/Dorsiflexion, as outlined above.

Appendix B – Statistical Tables

Table 13: Tukey Comparison Table for Isokinetic – Active (P/D)

			Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
ROM	Modified Skate	One95	16.7	2.9	0.00	9.4	24.0
		Shoe	-12.9	2.9	0.00	-20.2	-5.6
	One95	Modified Skate	-16.7	2.9	0.00	-24.0	-9.4
		Shoe	-29.6	2.9	0.00	-36.8	-22.3
	Shoe	Modified Skate	12.9	2.9	0.00	5.6	20.2
		One95	29.6	2.9	0.00	22.3	36.8
torque max	Modified Skate	One95	1.5	11.3	0.99	-26.5	29.4
		Shoe	-6.5	11.3	0.83	-34.5	21.5
	One95	Modified Skate	-1.5	11.3	0.99	-29.4	26.5
		Shoe	-7.9	11.3	0.76	-35.9	20.0
	Shoe	Modified Skate	6.5	11.3	0.83	-21.5	34.5
		One95	7.9	11.3	0.76	-20.0	35.9
torque min	Modified Skate	One95	0.0	1.9	1.00	-4.7	4.8
		Shoe	-2.6	1.9	0.38	-7.3	2.1
	One95	Modified Skate	0.0	1.9	1.00	-4.8	4.7
		Shoe	-2.6	1.9	0.37	-7.4	2.1
	Shoe	Modified Skate	2.6	1.9	0.38	-2.1	7.3
		One95	2.6	1.9	0.37	-2.1	7.4
Total work	Modified Skate	One95	3961.8	1766.6	0.08	-418.4	8342.0
		Shoe	-3376.4	1766.6	0.15	-7756.5	1003.8
	One95	Modified Skate	-3961.8	1766.6	0.08	-8342.0	418.4
		Shoe	-7338.1	1766.6	0.00	-11718.3	-2958.0
	Shoe	Modified Skate	3376.4	1766.6	0.15	-1003.8	7756.5
		One95	7338.1	1766.6	0.00	2958.0	11718.3

Table 14: Tukey Comparison table for Isokinetic – Passive (P/D)

			Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
torque_ROM	Modified Skate	One95	17.0	2.9	1.1E-05	9.7	24.3
		Shoe	-13.6	2.9	2.4E-04	-20.9	-6.3
	One95	Modified Skate	-17.0	2.9	1.1E-05	-24.3	-9.7
		Shoe	-30.6	2.9	5.3E-09	-37.9	-23.3
	Shoe	Modified Skate	13.6	2.9	2.4E-04	6.3	20.9
		One95	30.6	2.9	5.3E-09	23.3	37.9
Torque Max	Modified Skate	One95	1.0	1.5	7.8E-01	-2.7	4.8
		Shoe	5.5	1.5	3.4E-03	1.7	9.2
	One95	Modified Skate	-1.0	1.5	7.8E-01	-4.8	2.7
		Shoe	4.5	1.5	1.8E-02	0.7	8.2
	Shoe	Modified Skate	-5.5	1.5	3.4E-03	-9.2	-1.7
		One95	-4.5	1.5	1.8E-02	-8.2	-0.7
Torque Min	Modified Skate	One95	8.6	2.2	1.4E-03	3.2	14.0
		Shoe	-5.4	2.2	4.9E-02	-10.9	0.0
	One95	Modified Skate	-8.6	2.2	1.4E-03	-14.0	-3.2
		Shoe	-14.1	2.2	2.0E-06	-19.5	-8.7
	Shoe	Modified Skate	5.4	2.2	4.9E-02	0.0	10.9
		One95	14.1	2.2	2.0E-06	8.7	19.5

Table 15: Tukey Comparison for Isokinetic – Active (I/E)

			Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
ROM	Modified Skate	One95	1.1	5.5	.977	-12.4	14.6
		Shoe	-41.6	5.5	.000	-55.1	-28.1
	One95	Modified Skate	-1.1	5.5	.977	-14.6	12.4
		Shoe	-42.7	5.5	.000	-56.2	-29.2
	Shoe	Modified Skate	41.6	5.5	.000	28.1	55.1
		One95	42.7	5.5	.000	29.2	56.2
Torque Max	Modified Skate	One95	1.3	1.9	.794	-3.5	6.1
		Shoe	0.8	1.9	.907	-4.0	5.6
	One95	Modified Skate	-1.3	1.9	.794	-6.1	3.5
		Shoe	-0.4	1.9	.972	-5.2	4.4
	Shoe	Modified Skate	-0.8	1.9	.907	-5.6	4.0
		One95	0.4	1.9	.972	-4.4	5.2
Torque Min	Modified Skate	One95	-2.4	3.1	.736	-10.1	5.4
		Shoe	4.1	3.1	.411	-3.7	11.8
	One95	Modified Skate	2.4	3.1	.736	-5.4	10.1
		Shoe	6.4	3.1	.121	-1.4	14.2
	Shoe	Modified Skate	-4.1	3.1	.411	-11.8	3.7
		One95	-6.4	3.1	.121	-14.2	1.4
Total Work	Modified Skate	One95	1283.3	1141.6	.508	-1547.2	4113.8
		Shoe	-5601.7	1141.6	.000	-8432.2	-2771.1
	One95	Modified Skate	-1283.3	1141.6	.508	-4113.8	1547.2
		Shoe	-6885.0	1141.6	.000	-9715.5	-4054.4
	Shoe	Modified Skate	5601.7	1141.6	.000	2771.1	8432.2
		One95	6885.0	1141.6	.000	4054.4	9715.5

Table 16: Tukey Comparison for Isokinetic – Passive (I/E)

			Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
ROM	Modified Skate	One95	4.1	6.1	.781	-10.9	19.1
		Shoe	-38.2	6.1	.000	-53.2	-23.2
	One95	Modified Skate	-4.1	6.1	.781	-19.1	10.9
		Shoe	-42.3	6.1	.000	-57.3	-27.3
	Shoe	Modified Skate	38.2	6.1	.000	23.2	53.2
		One95	42.3	6.1	.000	27.3	57.3
Torque Max	Modified Skate	One95	-0.7	1.2	.818	-3.6	2.2
		Shoe	5.7	1.2	.000	2.8	8.5
	One95	Modified Skate	0.7	1.2	.818	-2.2	3.6
		Shoe	6.4	1.2	.000	3.5	9.2
	Shoe	Modified Skate	-5.7	1.2	.000	-8.5	-2.8
		One95	-6.4	1.2	.000	-9.2	-3.5
Torque Min	Modified Skate	One95	-0.4	1.3	.955	-3.7	2.9
		Shoe	-8.4	1.3	.000	-11.7	-5.1
	One95	Modified Skate	0.4	1.3	.955	-2.9	3.7
		Shoe	-8.0	1.3	.000	-11.3	-4.7
	Shoe	Modified Skate	8.4	1.3	.000	5.1	11.7
		One95	8.0	1.3	.000	4.7	11.3

Table 17: Significance F-Tables for Kinematic Data

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Noncent. Parameter	Observed Power[b]
Corrected Model	RAnkleAngles_x_ROM	99.820[a]	1	99.820	2.922	.118	2.922	.340
	RAnkleAngles_x_max	52.334[c]	1	52.334	.559	.472	.559	.104
	RAnkleAngles_x_min	296.708[d]	1	296.708	11.650	.007	11.650	.867
	RAnkleAngles_y_ROM	.017[e]	1	.017	.005	.944	.005	.050
	RAnkleAngles_y_max	1.442[f]	1	1.442	.028	.871	.028	.053
	RAnkleAngles_y_min	1.777[g]	1	1.777	.041	.843	.041	.054
	RAnkleAngles_z_ROM	1.211[h]	1	1.211	.076	.789	.076	.057
	RAnkleAngles_z_max	9.883[i]	1	9.883	.218	.650	.218	.071
	RAnkleAngles_z_min	4.175[j]	1	4.175	.046	.834	.046	.054
	RHipAngles_x_ROM	20.700[k]	1	20.700	.123	.733	.123	.062
	RHipAngles_x_max	.043[l]	1	.043	.000	.990	.000	.050
	RHipAngles_x_min	18.846[m]	1	18.846	.288	.603	.288	.078
	RHipAngles_y_ROM	6.452[n]	1	6.452	.226	.645	.226	.072
	RHipAngles_y_max	74.007[o]	1	74.007	.703	.422	.703	.118
	RHipAngles_y_min	124.162[p]	1	124.162	1.958	.192	1.958	.245

	RHipAngles_z_ROM	3.847[q]	1	3.847	.071	.795	.071	.057
	RHipAngles_z_max	87.161[r]	1	87.161	1.431	.259	1.431	.192
	RHipAngles_z_min	54.384[s]	1	54.384	.604	.455	.604	.109
	RKneeAngles_x_ROM	41.591[t]	1	41.591	.299	.597	.299	.079
	RKneeAngles_x_max	.929[u]	1	.929	.041	.844	.041	.054
	RKneeAngles_x_min	54.951[v]	1	54.951	.284	.606	.284	.077
	RKneeAngles_y_ROM	.337[w]	1	.337	.005	.947	.005	.050
	RKneeAngles_y_max	.205[x]	1	.205	.002	.964	.002	.050
	RKneeAngles_y_min	.016[y]	1	.016	.001	.975	.001	.050
	RKneeAngles_z_ROM	46.038[z]	1	46.038	1.401	.264	1.401	.189
	RKneeAngles_z_max	1.707[aa]	1	1.707	.060	.811	.060	.056
	RKneeAngles_z_min	30.017[ab]	1	30.017	.428	.528	.428	.091
Intercept	RAnkleAngles_x_ROM	17387.254	1	17387.254	509.048	.000	509.048	1.000
	RAnkleAngles_x_max	12110.389	1	12110.389	129.245	.000	129.245	1.000
	RAnkleAngles_x_min	475.830	1	475.830	18.683	.002	18.683	.973
	RAnkleAngles_y_ROM	210.794	1	210.794	62.829	.000	62.829	1.000
	RAnkleAngles_y_max	735.477	1	735.477	14.059	.004	14.059	.921
	RAnkleAngles_y_min	158.783	1	158.783	3.706	.083	3.706	.413
	RAnkleAngles_z_ROM	1102.558	1	1102.558	69.067	.000	69.067	1.000

	RAnkleAngles_z_max	112.524	1	112.524	2.487	.146	2.487	.297
	RAnkleAngles_z_min	510.626	1	510.626	5.668	.039	5.668	.575
	RHipAngles_x_ROM	42773.488	1	42773.488	255.085	.000	255.085	1.000
	RHipAngles_x_max	31573.930	1	31573.930	119.683	.000	119.683	1.000
	RHipAngles_x_min	848.381	1	848.381	12.982	.005	12.982	.900
	RHipAngles_y_ROM	5944.570	1	5944.570	208.257	.000	208.257	1.000
	RHipAngles_y_max	37.889	1	37.889	.360	.562	.360	.085
	RHipAngles_y_min	6931.631	1	6931.631	109.297	.000	109.297	1.000
	RHipAngles_z_ROM	9161.012	1	9161.012	169.558	.000	169.558	1.000
	RHipAngles_z_max	1492.737	1	1492.737	24.508	.001	24.508	.993
	RHipAngles_z_min	3257.809	1	3257.809	36.162	.000	36.162	1.000
	RKneeAngles_x_ROM	47503.778	1	47503.778	341.395	.000	341.395	1.000
	RKneeAngles_x_max	48601.968	1	48601.968	2145.488	.000	2145.488	1.000
	RKneeAngles_x_min	6.275	1	6.275	.032	.861	.032	.053
	RKneeAngles_y_ROM	5083.988	1	5083.988	69.957	.000	69.957	1.000
	RKneeAngles_y_max	5298.089	1	5298.089	54.735	.000	54.735	1.000
	RKneeAngles_y_min	2.208	1	2.208	.137	.719	.137	.063
	RKneeAngles_z_ROM	6325.432	1	6325.432	192.499	.000	192.499	1.000
	RKneeAngles_z_max	2270.135	1	2270.135	80.019	.000	80.019	1.000

	RKneeAngles_z_min	1016.758	1	1016.758	14.492	.003	14.492	.928
ConditionDROM1one952	RAnkleAngles_x_ROM	99.820	1	99.820	2.922	.118	2.922	.340
	RAnkleAngles_x_max	52.334	1	52.334	.559	.472	.559	.104
	RAnkleAngles_x_min	296.708	1	296.708	11.650	.007	11.650	.867
	RAnkleAngles_y_ROM	.017	1	.017	.005	.944	.005	.050
	RAnkleAngles_y_max	1.442	1	1.442	.028	.871	.028	.053
	RAnkleAngles_y_min	1.777	1	1.777	.041	.843	.041	.054
	RAnkleAngles_z_ROM	1.211	1	1.211	.076	.789	.076	.057
	RAnkleAngles_z_max	9.883	1	9.883	.218	.650	.218	.071
	RAnkleAngles_z_min	4.175	1	4.175	.046	.834	.046	.054
	RHipAngles_x_ROM	20.700	1	20.700	.123	.733	.123	.062
	RHipAngles_x_max	.043	1	.043	.000	.990	.000	.050
	RHipAngles_x_min	18.846	1	18.846	.288	.603	.288	.078
	RHipAngles_y_ROM	6.452	1	6.452	.226	.645	.226	.072
	RHipAngles_y_max	74.007	1	74.007	.703	.422	.703	.118
	RHipAngles_y_min	124.162	1	124.162	1.958	.192	1.958	.245
	RHipAngles_z_ROM	3.847	1	3.847	.071	.795	.071	.057
	RHipAngles_z_max	87.161	1	87.161	1.431	.259	1.431	.192
	RHipAngles_z_min	54.384	1	54.384	.604	.455	.604	.109

	RKneeAngles_x_ROM	41.591	1	41.591	.299	.597	.299	.079
	RKneeAngles_x_max	.929	1	.929	.041	.844	.041	.054
	RKneeAngles_x_min	54.951	1	54.951	.284	.606	.284	.077
	RKneeAngles_y_ROM	.337	1	.337	.005	.947	.005	.050
	RKneeAngles_y_max	.205	1	.205	.002	.964	.002	.050
	RKneeAngles_y_min	.016	1	.016	.001	.975	.001	.050
	RKneeAngles_z_ROM	46.038	1	46.038	1.401	.264	1.401	.189
	RKneeAngles_z_max	1.707	1	1.707	.060	.811	.060	.056
	RKneeAngles_z_min	30.017	1	30.017	.428	.528	.428	.091
Error	RAnkleAngles_x_ROM	341.564	10	34.156				
	RAnkleAngles_x_max	937.014	10	93.701				
	RAnkleAngles_x_min	254.689	10	25.469				
	RAnkleAngles_y_ROM	33.550	10	3.355				
	RAnkleAngles_y_max	523.143	10	52.314				
	RAnkleAngles_y_min	428.407	10	42.841				
	RAnkleAngles_z_ROM	159.636	10	15.964				
	RAnkleAngles_z_max	452.494	10	45.249				
	RAnkleAngles_z_min	900.855	10	90.085				
	RHipAngles_x_ROM	1676.830	10	167.683				

	RHipAngles_x_max	2638.137	10	263.814				
	RHipAngles_x_min	653.503	10	65.350				
	RHipAngles_y_ROM	285.443	10	28.544				
	RHipAngles_y_max	1053.377	10	105.338				
	RHipAngles_y_min	634.199	10	63.420				
	RHipAngles_z_ROM	540.287	10	54.029				
	RHipAngles_z_max	609.090	10	60.909				
	RHipAngles_z_min	900.896	10	90.090				
	RKneeAngles_x_ROM	1391.460	10	139.146				
	RKneeAngles_x_max	226.531	10	22.653				
	RKneeAngles_x_min	1935.658	10	193.566				
	RKneeAngles_y_ROM	726.727	10	72.673				
	RKneeAngles_y_max	967.956	10	96.796				
	RKneeAngles_y_min	160.684	10	16.068				
	RKneeAngles_z_ROM	328.595	10	32.859				
	RKneeAngles_z_max	283.701	10	28.370				
	RKneeAngles_z_min	701.601	10	70.160				
Total	RAnkleAngles_x_ROM	17828.638	12					
	RAnkleAngles_x_max	13099.737	12					

	RAnkleAngles_x_min	1027.227	12					
	RAnkleAngles_y_ROM	244.362	12					
	RAnkleAngles_y_max	1260.062	12					
	RAnkleAngles_y_min	588.967	12					
	RAnkleAngles_z_ROM	1263.404	12					
	RAnkleAngles_z_max	574.901	12					
	RAnkleAngles_z_min	1415.656	12					
	RHipAngles_x_ROM	44471.019	12					
	RHipAngles_x_max	34212.111	12					
	RHipAngles_x_min	1520.730	12					
	RHipAngles_y_ROM	6236.466	12					
	RHipAngles_y_max	1165.274	12					
	RHipAngles_y_min	7689.991	12					
	RHipAngles_z_ROM	9705.146	12					
	RHipAngles_z_max	2188.988	12					
	RHipAngles_z_min	4213.089	12					
	RKneeAngles_x_ROM	48936.830	12					
	RKneeAngles_x_max	48829.428	12					
	RKneeAngles_x_min	1996.884	12					

	RKneeAngles_y_ROM	5811.052	12					
	RKneeAngles_y_max	6266.250	12					
	RKneeAngles_y_min	162.908	12					
	RKneeAngles_z_ROM	6700.065	12					
	RKneeAngles_z_max	2555.543	12					
	RKneeAngles_z_min	1748.377	12					
Corrected Total	RAnkleAngles_x_ROM	441.384	11					
	RAnkleAngles_x_max	989.348	11					
	RAnkleAngles_x_min	551.397	11					
	RAnkleAngles_y_ROM	33.568	11					
	RAnkleAngles_y_max	524.585	11					
	RAnkleAngles_y_min	430.184	11					
	RAnkleAngles_z_ROM	160.847	11					
	RAnkleAngles_z_max	462.377	11					
	RAnkleAngles_z_min	905.030	11					
	RHipAngles_x_ROM	1697.530	11					
	RHipAngles_x_max	2638.181	11					
	RHipAngles_x_min	672.349	11					
	RHipAngles_y_ROM	291.895	11					

	RHipAngles_y_max	1127.385	11					
	RHipAngles_y_min	758.360	11					
	RHipAngles_z_ROM	544.135	11					
	RHipAngles_z_max	696.251	11					
	RHipAngles_z_min	955.280	11					
	RKneeAngles_x_ROM	1433.052	11					
	RKneeAngles_x_max	227.460	11					
	RKneeAngles_x_min	1990.609	11					
	RKneeAngles_y_ROM	727.064	11					
	RKneeAngles_y_max	968.161	11					
	RKneeAngles_y_min	160.701	11					
	RKneeAngles_z_ROM	374.633	11					
	RKneeAngles_z_max	285.408	11					
	RKneeAngles_z_min	731.618	11					

Table 18: Significance F-table for kinetic data

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Noncent. Parameter	Observed Powerb
Corrected Model	Fx_max	90.5	1.0	90.5	.03	.86	0.0	0.1
	Fy_max	306.0	1.0	306.0	1.93	.20	1.9	0.2
	Fy_min	342.3	1.0	342.3	.14	.71	0.1	0.1
	Fz_max	302.8	1.0	302.8	.02	.90	0.0	0.1
Intercept	Fx_max	6216814.7	1.0	6216814.7	2176.66	.00	2176.7	1.0
	Fy_max	16348.4	1.0	16348.4	103.99	.00	104.0	1.0
	Fy_min	680165.5	1.0	680165.5	291.22	.00	291.2	1.0
	Fz_max	19572990.6	1.0	19572990.6	1316.18	.00	1316.2	1.0
ConditionDROM1one952	Fx_max	90.5	1.0	90.5	.03	.86	0.0	0.1
	Fy_max	306.0	1.0	306.0	1.95	.19	1.9	0.2
	Fy_min	342.3	1.0	342.3	.15	.71	0.1	0.1
	Fz_max	302.8	1.0	302.8	.02	.90	0.0	0.1
Error	Fx_max	28561.3	10.0	2856.1				
	Fy_max	1572.1	10.0	157.2				
	Fy_min	23355.8	10.0	2335.6				
	Fz_max	148710.6	10.0	14871.1				
Total	Fx_max	6245466.4	12.0					
	Fy_max	18226.5	12.0					
	Fy_min	703863.6	12.0					
	Fz_max	19722004.0	12.0					
Corrected Total	Fx_max	28651.7	11.0					
	Fy_max	1878.1	11.0					
	Fy_min	23698.1	11.0					
	Fz_max	149013.4	11.0					

Appendix C – Information and Consent Document

INFORMATION AND CONSENT DOCUMENT

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Biomechanics Laboratory, Department of Kinesiology and Physical Education, McGill University

Statement of Invitation

You are invited to participate in a research project conducted by the above named investigator(s). This research project will be performed in the Exercise Physiology Laboratory of the Department of Kinesiology and Physical Education, McGill University, located at 309 Pine Ave West, Montréal, Québec H2W 1S4. You are asked to come to one experimental session that will each last up to 1 hour. We greatly appreciate your interest in our work.

Purpose of the Study

The purpose of this study is to quantify ice hockey boot stiffness properties while simulating movements similar to a skating stride using the Biodex System 4 Pro. The results of this study will lead to a better understanding of the kinematics of the ankle boot complex during an ice skating stride, as well as pressure points within boot models. These results may then lead to discernable differences in different boot models, as well as quantified information about the interaction of the foot and the skate boot.

Your participation in this study involves:

Providing informed consent prior to the experimental session, Performing three to five repetitions of plantar/dorsi flexion and inversion eversion movements on a Biodex System 4 Pro machine using a pair of running shoes and various skate models.

The procedure listed below are common to the experimental session:

You foot will be outfitted with pressure sensors to track pressure points in the skate boot

You will be asked to complete a preliminary trial to get familiarized with the required tasks

You will be asked to conduct 1 trial per task

1. You will be required to return at a later scheduled date for phase two of this project; a skating push off on a synthetic surface in lab

Risks and Discomforts

It is envisioned that you will encounter no significant discomfort during these experiments. You will be given a control button that starts the trial when you are ready and stops the trial in the event that you feel any discomfort.

Benefits

There are no personal benefits to be derived from participating in this study. Determining the kinematics of the ankle and skate boot complex will add depth to the general understanding of a skating stride, as well as to influence future product designs.

Confidentiality

All the personal information collected during the study you concerning will be encoded in order to keep their confidentiality. These records will be maintained at the Biomechanics Laboratory by Dr. David Pearsall for 5 years after the end of the project, and will be destroyed afterwards. Only members of the research team will be able to access them. In case of presentation or publication of the results from this study nothing will enable your identification.

Inquiries Concerning this Study

If you require information concerning the study (experimental procedures or other details), please do not hesitate to contact *Zubair Baig* or *Jonathan Albrecht,* at the email addresses listed at the top of this document.

Responsibility clause

In accepting to participate in this study, you will not relinquish any of your rights and you will not liberate the researchers nor their sponsors or the institutions involved from any of their legal or professional obligations.

Consent

Please be advised that your participation in this research undertaking is strictly on a voluntary basis, and you may withdraw at any time.

A copy of this form will be given to you before the end of the experimental session.

CONSENT

I, ___________________________________, AGREE TO VOLUNTARILY PARTICIPATE IN THE STUDY DESCRIBED ABOVE ABOUT THE KINEMATICS AND KINETICS OF ICE HOCKEY SKATING

I HAVE RECEIVED AND READ A DETAILED DESCRIPTION OF THE EXPERIMENTAL PROTOCOL. I AM FULLY SATISFIED WITH THE EXPLANATIONS THAT WERE GIVEN TO ME REGARDING THE NATURE OF THIS RESEARCH PROJECT, INCLUDING THE POTENTIAL RISKS AND DISCOMFORTS RELATED TO MY PARTICIPATION IN THIS STUDY.

I am aware that I have the right to withdraw my consent and discontinue my participation at any time without any prejudices.

Signatures

SUBJECT