Fit Performance and Responsiveness of Ice Hockey Goaltender Leg Pads

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Abstract

Ice hockey goaltenders wear large leg pads that protect from blunt trauma but also permit a goaltender to adopt common save positions like the butterfly. Leg pad models use different constructions to make pads stiff or flexible. The purpose of this project was to determine if there were butterfly fit, responsiveness, and performance differences between three leg pad conditions while performing the butterfly save position. Three goaltender leg pad conditions were used: stiff pad with elastic toe strap, stiff pad with lace toe strap and flexible pad with lace toe strap. Leg pad conditions tested similarly in anterior-posterior fit, responsiveness, and performance. The similarity in leg pad ~~r~~esponsiveness, and performance may have occurred because all leg pads are built to the same limiting standards. There were moderate superior-inferior fit effects between the flexible and stiff leg pad conditions with goaltenders landing slightly lower on the knee stack in the stiff leg pad conditions. However, this was a small difference and participants were observed to land on the inferior 25% of the knee stack in all leg pad conditions indicating that there may be a need to improve leg pad fit.

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Chapter 1: Introduction

Ice hockey goaltending equipment has progressed since the sport was invented nearly 150 years ago (IIHF, 2008). Advances in materials and design engineering have led to innovative leg pad constructions that contribute to goaltending success. Leg pads have different features that can impact a goaltender's playing ability. For example, a stiff leg pad features high density foams and a structurally stiff construction that allows for stability, sliding, seal along the ice and high rebound velocity. Flexible leg pad constructions are created in a similar fashion to the stiff leg pad but use slightly less dense foams and structural breaks in construction that allow for increased flexion throughout the leg pad. The softer construction of flexible leg pads allow for more rebound control and pad flexibility as the goaltender moves.

Goaltender tactics and techniques have changed over time along with equipment development. Today one particular save technique, the butterfly, is used upwards of 32 times during a game (Bell et al., 2008) and 300 times during a practice (Epstein et al., 2013). This save technique involves goaltenders dropping quickly to their knees and flaring their lower legs outwards to cover the bottom of the net. This technique allows them to block low shots while keeping their upper body mobile to block or catch higher shots. Other techniques such as the reverse horizontal (RVH) are modified versions of the butterfly that are used in certain circumstances close or at the side of the net. Goaltenders spend a lot of time in the butterfly, or similar positions;

therefore, it is essential that modern equipment fits, responds, and performs at a high level to allow goaltenders to play their position effectively and safely.

Understanding the differences between pad constructions and toe strap options can help equipment manufacturers stay on the leading edge of equipment production as well as help goaltenders improve their performance. This research study aimed to measure differences in fit, responsiveness and performance between stiff and flexible leg pad constructions and toe strap options. Leg pad performance differences were measured using peak butterfly drop velocity. Responsiveness testing was quantified by determining the pad's reaction time to the goaltender's initiation of the butterfly movement. Fit was quantified by identifying the knee center of pressure on the knee stack (the medial knee padding) during the butterfly drop movement. It was hypothesized that the stiff pad construction would display faster drop velocity, decreased fit and less responsiveness compared to the flexible pad construction. A secondary hypothesis was that an elastic toe strap condition will improve responsiveness outcomes compared to a lace toe strap condition but will not significantly affect fit or performance outcomes.

Chapter 2: Literature Review

2.1 Global Reach

Ice hockey was started as a winter pastime by James Creighton in Montreal in 1873 (IIHF, 2008). Since the sport's inception, the game has grown to become popular around the world. Today, over 80 countries are members of the International Ice Hockey Federation (IIHF, n.d.), the global governing body for international ice hockey. North America is home to the highest level of professional hockey in the world, the National Hockey League (NHL). As the sport grows, professional leagues are becoming more prevalent in many other countries. In international competition North American and European countries have traditionally been very successful; however, other countries are starting to become increasingly competitive at international events. The global growth of ice hockey has led to a need to increase the amount of research into factors that impact athletes.

2.2 Ice Hockey Game Play

By NHL rules and regulations, the sport of ice hockey is played on a sheet of ice that is 60.96m long and 25.91m wide with rounded corners, boards surrounding the ice, and glass extending from the boards in most areas of the playing surface (NHL, 2020). For games played in IIHF competitions, the rink is wider than that of the NHL measuring 60m long and 31m wide (IIHF, 2016) but has similar board and glass rules. At each end of the rink there is a goal net. The goal net is 4-feet tall and 6-feet-wide with mesh covering the back.

A game of ice hockey is 60 minutes in duration with two intermissions (three 20-minute periods: NHL, 2020). This is like other team sports such as basketball, or soccer in that the game is played for a certain amount of time, rather than to a pre-determined score. During a game each team can have a maximum of 20 players who are available to play. Most often, two of these players are goaltenders, six are defensemen, and 12 are forwards. At one time, six players from each team can be on the ice surface. This usually includes one goaltender, and five skaters (forwards and defencemen) (NHL, 2020).

Figure 1. Alexander Ovechkin shooting a puck towards the opposing goal demonstrating the flexion of the stick and how the blade interacts with the puck.

Ice hockey is a fast and physical sport that comes with a risk of injuries during play (McKay et al., 2014). Players are equipped with protective equipment that covers most of their bodies, bladed skates that are used to propel themselves along the ice surface and a stick that is used to control the puck. The puck is 1 inch thick, 3 inches in diameter and made of vulcanized rubber (NHL, 2020). To move the puck around the ice players use hockey sticks (Worobets et al., 2006). Hockey sticks are long and rectangular with varying stiffness profiles and a flattened blade at the bottom that is used to interact with the hockey puck as shown by Alex Ovechkin (Figure 1).

The overall objective of ice hockey is to score more goals than the opposing team. A goal is scored when a team can propel the puck into the other team's net. To score goals, and to prevent the other team from scoring, teams use various techniques and tactics. When a team has possession of the puck, they are on offence and try to create opportunities to score. When a team does not have possession of the puck, they are on defence and try to prevent the other team from scoring until they can regain possession of the puck. During a game teams try to generate shots with the objective of scoring goals. While defensive tactics and skaters deflecting or blocking shots reduces this number, many shots still end up making it to the net. This is where the role of the goaltender comes into play as they attempt to block the opposition's shots on goal.

2.3 Goaltending

Figure 2. Goaltender Corey Crawford wearing goaltending equipment.

The goaltender is last line of defence for an ice hockey team. They are the only players who often stay on the ice surface for the entire game without substitutions. They remain near their goal for the duration of the game in an exclusively defensive role. Goaltenders aim to block the opposition's shots to prevent the puck from entering their net and the other team from scoring. Every shot they stop is counted as a save. To increase the number of saves they make and reduce the number of goals scored against them, goaltenders assume save techniques that allow them to cover as much of the net as possible. To achieve these techniques and maintain their safety, goaltenders wear position specific padding that is larger with increased protective capabilities compared to skaters' equipment as shown by Corey Crawford (Figure 2).

2.4 Goaltending Equipment History and Innovation

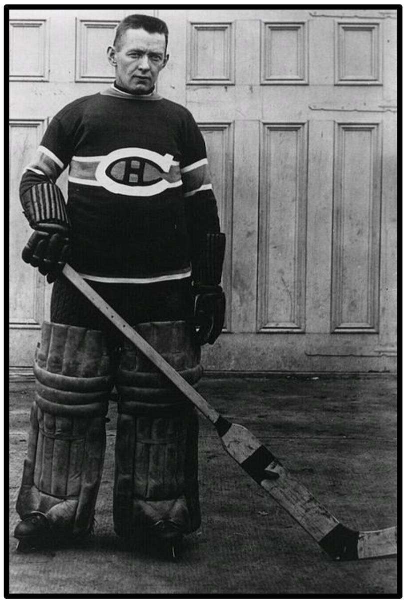


Figure 3. Georges Vezina during the early 1920's equipped with goaltender equipment of that time.

The concept of the goaltender wearing more equipment and defending the team's goal has been present throughout hockey's history as shown by Georges Vezina (Figure 3) who played the sport in the 1920's. Key figures throughout hockey's history have had profound effects on the goaltending equipment, techniques, and tactics that are present in the game today.

One of the biggest events in ice hockey goaltending history occurred when Jacques Plante, who played in the NHL from 1952 to 1973, first wore a facemask during a game (Coffee, 2017). Plante (Figure 4) introduced a way for goaltenders to play the game in a safer way and started an early revolution in goaltender equipment. Prior to Plante, goaltenders would play most of the game in a standing position to avoid facial injury. While remaining in their more upright position, goaltenders would kick their legs laterally to block oncoming low shots. For high shots they would use their catching or blocking glove to stop the puck. The face mask allowed goaltenders to use save techniques that are lower to the ice with reduced facial injury risk.

More recently, with further development of more protective helmets, facial injuries have only been observed in 4.07 out of 10 000 athlete exposures among NHL goaltenders (Keshen et al., 2020). This allowed athletes to further progress goaltending tactics that were instrumental in the early days of goaltender equipment development.

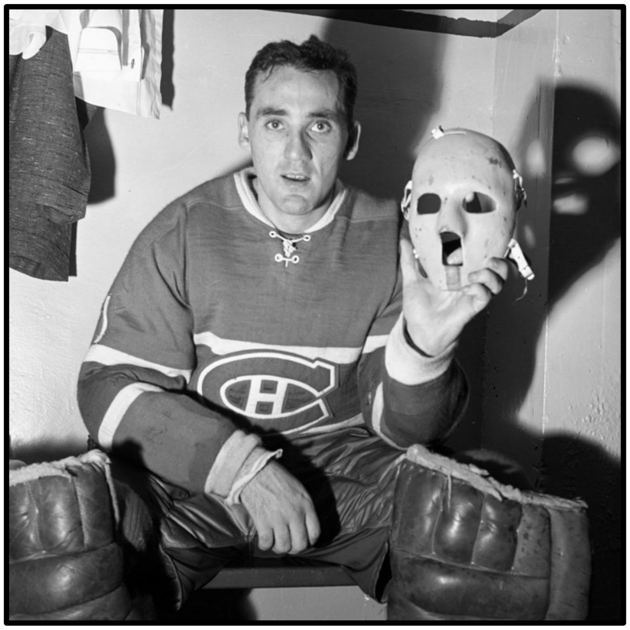


Figure 4. Jacques Plante, the first goaltender to wear a facemask in the NHL, with a model of his facemask.

Along with equipment developments, tactical advances in the goaltender position have played a part in developing the goaltending position. Glenn Hall (Figure 5), who played in the NHL from 1952-1971 introduced what is now known as the butterfly save technique (Verdi, 2017). During a time where goaltenders played in a mostly standing position, Hall would drop to his knees and rotate his hips internally to flare his lower legs. This allowed Hall to cover the bottom of the goal more effectively than standing up and trying to kick pucks away. Though introduced by Hall, the butterfly technique was later popularized by Patrick Roy and his coach Francois Allaire when he started his NHL career in 1985.

Today, the butterfly save technique is a foundational goaltending technique and is used regularly during practices and games (Bell et al., 2008; Epstein et al., 2013).

Figure 5. Glenn Hall (left) in the butterfly save technique. Hall is considered the pioneer of the butterfly technique. The introduction of the butterfly save technique heavily influenced how modern goaltenders play their position. Modified from (Hockey Writers Archives). Cam Talbot (right) a current goaltender wearing modern equipment in the butterfly save technique.

2.5 Equipment Development

The goaltending position has advanced through innovations in materials engineering as well as goaltenders modifying their playing strategy. Goaltenders practice and strategize with the goal of improving their performance. Their equipment can help them to perform at a high level. Equipment design and manufacturing companies employ teams of engineers, designers and researchers that share a common goal of creating equipment that will meet the needs to players and lead to success for their company. Feedback from athletes helps to influence equipment design.

When new equipment is created, athletes can use this new equipment to benefit from the newest design and technology. With new equipment innovation athletes can push the limits of the way they play by implementing new tactics and techniques that may have not been possible or safe with older versions of equipment. Progression of the position and adoption of new strategies can lead to new player demands, equipment designs and new materials which restarts the innovation cycle (Figure 6).

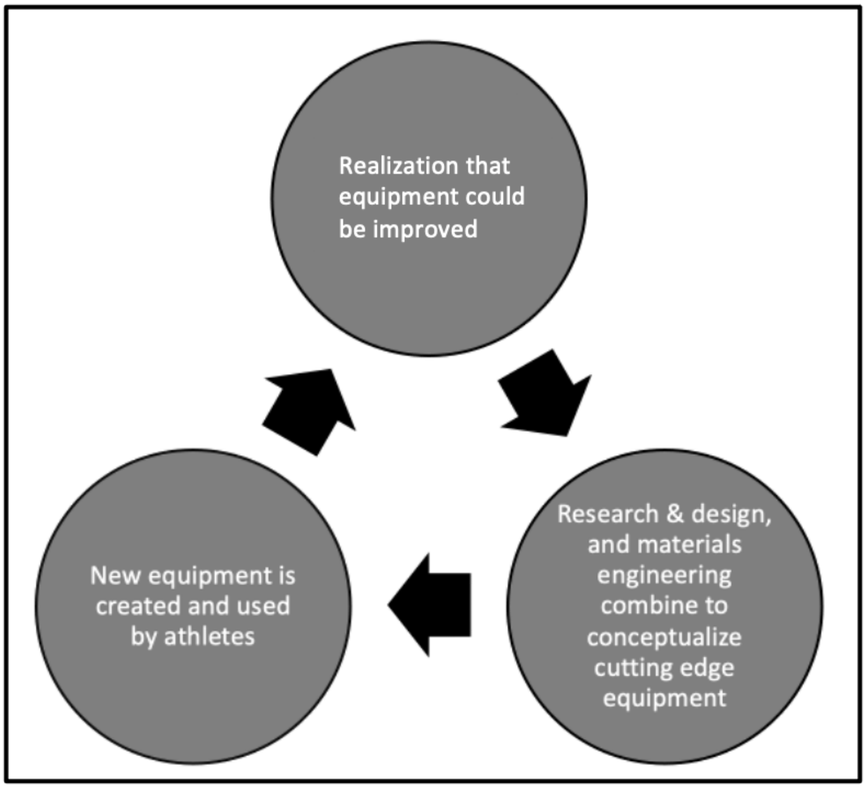


Figure 6. Depiction of the cyclic nature of equipment innovation ideology. Goaltenders use the current equipment. Athletes, researchers, coaches, or equipment developers identify areas that equipment can improve. Engineers, designers, and manufacturers collaborate to produce new models of equipment that benefit the player and manufacturing company.

Creating innovative and high performing goaltender equipment that meet the needs of athletes is important for athletes as well as the manufacturing company. Incorporating professional player input, along with a team of design, engineering, and manufacturing professionals can help the company remain on the forefront of equipment development.

Equipment companies look to use new innovations to improve their product and meet the needs of players, often with performance in mind (Frayne & Dickey, 2017). The rapid improvements that result from new equipment ideologies and manufacturing technologies can lead to gaps in the knowledge of a player's interaction with their equipment (Stefanyshyn & Wannop, 2015). It is important to understand these interactions to keep athletes safe and playing at the highest level.

2.6 Goaltending Equipment Today

Modern goaltending equipment is more advanced than ever before because of advancements in materials engineering and design. While the concept of goaltender equipment has remained similar, there has been large changes in equipment design as can be seen in Figure 7. Today, helmets are made of synthetic materials such as vinyl, fiberglass, carbon fiber, and Kevlar and protect goaltenders against puck impacts and contact with the ice (Clark et al., 2017; Keshen et al., 2020; Nur et al., 2015). To protect the trunk and upper limbs, large chest protectors are worn to limit the impact of pucks. A blocking glove that has a hard rectangular surface on the posterior aspect of the hand is used on the side in which a goaltender holds their stick. On the other hand, a catching glove which consists of protection and a deepened pocket located between the index finger and the thumb that is used to trap and control the puck. A goaltender stick is long with a curved blade, like that of a skater, but has a wider bottom half known as a paddle which assists a goaltender in blocking shots. For the lower body, goaltenders use protective pants that cover from below the ribs to above the knee. Their skates have increased protection from blunt forces and a longer blade. On their legs goaltenders wear large leg pads that are distinguishable from those of players of other positions. Beneath their leg pads, many goaltenders also wear additional knee guards.

Figure 7. Goaltenders Terry Sawchuk (left) and Phillpp Grubauer (right). Sawchuk played in the NHL from 1949 to 1970. Grubauer is a current NHL goaltender.

2.7 Leg Pad Overview

Leg pads can measure up to 27.9 cm in width, and the length must be proportional to the goaltender's height and have a maximum depth of 26.7 cm (NHL, 2020). A leg pad is composed of a large anterior surface, medial aspect padding, and a posterior strapping system as shown in Figure 8. The anterior surface of the pad is a rectangular surface that has an angled toe component, called the boot, that sits on top of the skate. There is also an outer roll that supports the shape and stiffness of the pad (Figure 9). The medial padding consists of layered foams creating padding that protects the knee and medial leg from ice impacts. This area is manufactured to also provide stability when a goaltender is moving around the goal in a kneeling position. The anterior and medial aspects of the pad are covered in polyurethane and hydrophobic synthetic leather to resist water absorption and reduce resistance while sliding. The posterior aspect of the leg pads have elastic strapping systems used to attach the pad to the lower leg. Additionally, there is a strap between the toe of the pad and the toe of the player’s skate known as the toe strap. These toe straps are often made from traditional skate laces; however, elastic toe straps have become another option for goaltenders today.

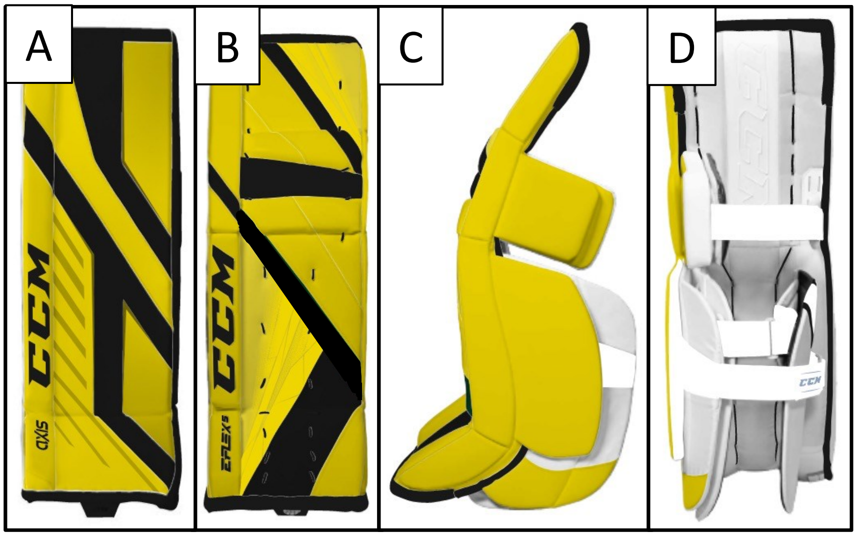


Figure 8. Goaltender leg pads from different view angles. A: Anterior surface of a stiff leg pad. B: Anterior surface of a flexible leg pad. C: Medial aspect of a leg pad. D: Posterior view of the leg pad showing strapping system.

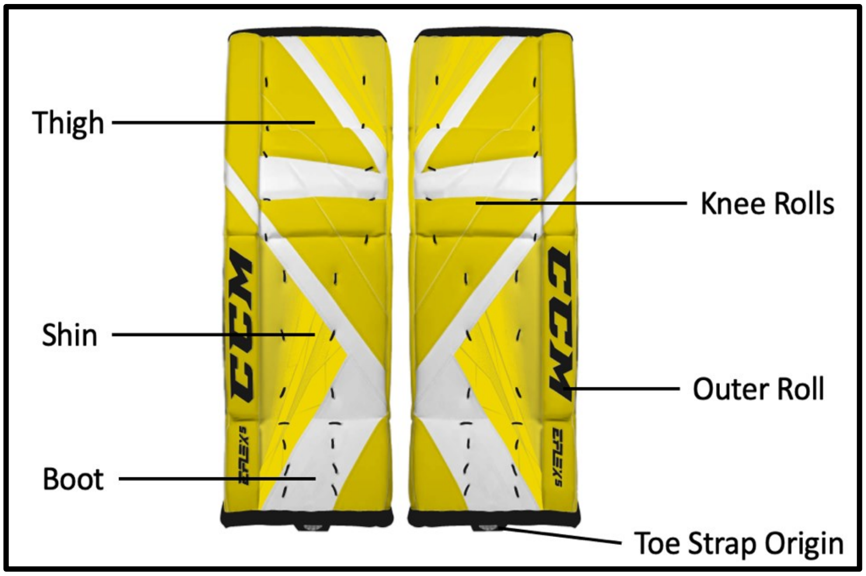


Figure 9. Anterior view of a leg pad with labels pointing to the thigh, shin, boot, knee roll, outer roll, and toe strap origin aspects of the leg pad.

2.8 Leg Pad Constructions

Although modern leg pads must follow strict NHL rules and regulations regarding sizing restrictions, there remain various leg pad constructions. Two current commercial options are the stiff leg pad and the flexible leg pad. While they feature different flexion profiles and fit, the two types of pads are created in a similar way. Modern leg pads start with a moulded core (Figure 10) that has a lower

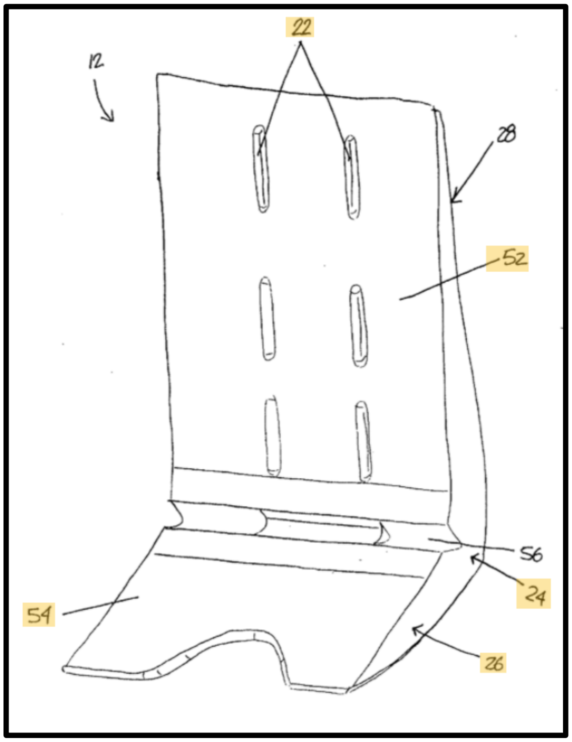


Figure 10. Concept image of the moulded foam core of a goaltender leg pad.

leg and foot component (Lefebvre, 2008). Posterior to this core, there is a leg channel where the player's lower leg sits and is surrounded by a strapping system. Anterior to the core, specialized foams are layered to create the front of the pad. This anterior side extends superiorly beyond the core to cover the athlete's knee and thigh (Lefebvre, 2008). Depending on the desired specifications of the pad, different density foams are utilized in the pad's anterior component. On the anterior surface and lateral edge of the pad, an outer roll is used to support the pad's structure. This roll can feature breaks to allow for increased flexibility. Medially, the knee stack features layers of foams to reduce impact when dropping to the ice, and its maximum measurements can be 7" long, 5 ½" high, and 2 ½" thick (NHL, 2020). Superficially, the knee stack has high density foams that create a harder surface that helps with sliding and stability.

2.9 Stiff Leg Pads

Current stiff leg pad constructions are designed to maintain their rigidity throughout a goaltender's motions. Shown on the left side of Figure 11a, these pads are more resistant to flexion in the sagittal plane (23° of flexion at the knee with 200 N of downwards axial force, 0.12°/N). This stiffness is provided by the internal structure of the pad. To allow for foot mobility, softer foams are inserted where the shin and boot of the leg pad meet.

2.10 Flexible Leg Pads

Flexible leg pad constructions, as seen in Figure 11b, have greater flexion within the sagittal plane compared to the stiff leg pad. (81° of flexion at the knee with 200 N of downwards axial force, 0.41°/N). The increased flexibility of these pads are a result of the internal leg pad construction. Flexible leg pads feature structural breaks (above and below the knee) and slightly lower density foams allowing for more flexion.

Figure 11. Current stiff (left) and flexible (right) pad constructions. The flexible construction has horizontal structural breaks in the outer roll and the anterior surface that help to increase the flexibility of the pad compared to the stiff construction.

2.11 Player - Leg Pad Interaction

A goaltender's ability to move efficiently and block an opponent's shot is vital for their success. Their equipment, which is bulky and surrounds their limbs, may affect their ability to perform. Therefore, goaltender equipment must be lightweight to repeatedly make saves without undue fatigue, be protective against shots, and allow enough mobility to assume the necessary save positions and react athletically. The fit and responsiveness of equipment in addition to a player's skill contributes to their ability to make saves.

To make saves, goaltenders move into save positions as quickly as possible. The butterfly save technique is the most frequently used save position (Bell et al., 2008). When a goaltender drops into the butterfly position their leg pads rotate externally around their lower leg to face anteriorly, towards incoming shots (Frayne & Dickey, 2017). Goaltenders land on the medial knee padding, known as the knee stack, when dropping into the butterfly position. The knee stack is important because it reduces the force of the impact to the knee during the ice contact. In addition to reducing the knee impact upon dropping into the butterfly, the medial aspect of the pad gives goaltenders a stable surface in which they can balance while performing movements from a kneeling position (Frayne & Dickey, 2017).

A toe strap connects the toe of the leg pad to the toe of the goaltender's skates (Figure 12). Often these are made of traditional skate lace. The lace toe strap helps to limit leg pad external rotation but offers little to help the pad return to a starting position leading to the suggestion that perhaps an elastic toe strap could be beneficial (Frayne & Dickey, 2017). It is unknown if using an elastic toe strap influences leg pad fit, performance or responsiveness during common movements such as the butterfly.

Understanding how different leg pad constructions and toe strap conditions affect a goaltender is important in further understanding how goaltenders interact with their equipment. Stefanyshyn & Wannop (2015) emphasized that progressing technologies often lead to the creation of advanced equipment; however, the biomechanical research that identifies how the equipment affects the athlete can fall behind. As equipment technology develops it is important to keep biomechanical research up to date to minimize gaps in our understanding of athlete safety and performance when wearing protective equipment (Stefanyshyn & Wannop, 2015).

Figure 12. The pads toe strap is tied around the front of the goaltender's skate to limit pad rotation.

Literature involving the effect of ice hockey goaltender equipment on athletes is limited. Comparisons can be made to firefighters who wear personal protective equipment (PPE) that covers their trunk and limbs. Firefighting PPE has been shown to reduce time to exhaustion and increase heart rate during a trial compared to a control (Smith et al., 2012). Goaltenders, who wear 15-20kg of equipment when they play (Frayne & Dickey, 2017), likely experience similar impacts of their equipment. Goaltenders wear PPE that covers their entire body. This can create physiological and metabolic stress on the body as their ability to dissipate heat is diminished. Goaltenders lose 2.9 ± 0.3 liters of fluid and 3.81 ± 0.21 grams of sodium per hour of playing which is higher than players of other positions (Palmer & Spriet, 2008) and this can reduce their goaltending performance (McCarthy et al., 2020). Therefore, it is imperative to understand the effects that equipment modifications may have on fit, responsiveness and performance because these can impact player safety and success.

2.12 Fit, Responsiveness, and Performance in Research

Research in the field of ice hockey goaltender biomechanics is lacking. Few studies have quantified the effect of ice hockey goaltending equipment on athlete biomechanics. Limited understanding of how varying equipment conditions impact an athlete's movements in an ice hockey goaltending context leaves gaps in knowledge when it comes to athletic performance and safety.

2.12.1 Performance

Ice hockey goaltenders need to move quickly to block incoming shots and prevent the opposing team from scoring. The ability to move into position to make a save faster is beneficial as a goaltender can block the shooter's target before the puck gets to the net. Other than skating, the butterfly save technique is the most common goaltender movement during a game (Bell et al., 2008). Therefore, quantifying how quickly a goaltender can get into this position in different types of leg pad is important. Frayne & Dickey (2017) concluded that pads with different constructions (flex profiles) and leg channel widths resulted in different peak butterfly drop velocities with more flexible pads resulting in faster velocities than stiff and control pads. They reported peak butterfly drop velocities between 2.82 m/s – 3.05 m/s depending on pad stiffness and leg channel width (Frayne & Dickey, 2017).

2.12.2 Responsiveness

Leg pads must closely move with the goaltender's lower limbs to ensure the goaltender is properly protected. If the leg pad trails the athlete when they start to move or continues moving when the athlete stops, the leg pad may not be able to protect the athlete. Additionally, larger movement differences between athlete and equipment could result in net coverage gaps, or improperly positioned equipment that could result in decreased performance. Determining if there are responsiveness differences between stiff and flexible leg pads or lace and elastic toe straps during common goaltending movements can help athletes understand how their equipment is working with them and identify potential areas of focus for manufacturers.

2.12.3 Fit

Goaltender leg pads are attached to the athlete's lower leg with a posterior strapping system. This strapping system allows for rotation of the pad about the lower leg in the transverse plane. This is important because as a goaltender drops to the ice, such as in a butterfly save position, their leg pads can rotate externally around the lower leg to keep the anterior surface facing oncoming shots. When they land on the ice, their knee lands on the medial knee stack (Figure 13). It is important that an athlete's leg pads fit correctly so that when they drop to their knees they land centrally on the knee stack and are not impacting the ice with their knee or lower leg.

Frayne & Dickey (2016) used pressure sensors lined along the medial knee stack to quantify impact forces as goaltenders dropped in the butterfly save technique. They did not intend to test the fit of pads. This pressure sensor setup can be used to measure fit by determining the knee centre of pressure (CoP) location with respect to the center of the knee stack.

Figure 13. Athlete's knee landing on the medial knee stack as the leg pad rotates laterally about the lower leg upon dropping into the butterfly save position.

2.13 Injury Risk

In addition to the risk from puck and player impacts, the body positions that goaltenders use to block shots can increase their risk of injury. The save positions that goaltenders use to be successful can be stressful on their bodies. Wörner et al. (2019), found that 69% of goaltenders experienced at least one incidence of hip injury during a season, most of which were a result of overuse. Per 60 minutes of playing time, Epstein et al. (2013) reported that goaltenders are at the same risk of hip injury as skaters; however, since goaltenders most often play the entire 60 minutes of a game, their risk per game is greater.

While performing the butterfly, goaltenders assume a position of hip flexion, hip internal rotation, and knee flexion. These joint motions, combined with a high frequency of the movement during practices and games (Bell et al., 2008; Epstein et al., 2013), leads to a high risk of overuse injuries in goaltenders. In the butterfly position hip internal rotation reaches an athlete's passive range of motion (Wijdicks et al., 2014). Repeated high magnitude hip internal rotations can contribute high rates of hip deformities among goaltenders (Mehta et al., 2019). 69.4% of elite goaltenders' hips showed cam-type deformity (Lerebours et al., 2016). Cam-type deformities are the result of growth of the femoral neck (Ito et al., 2001), which can lead to an abutment between the femoral neck and acetabulum causing damage to acetabular cartilage (Ganz et al., 2003). The impingement that happens at the hip is known as femoroacetabular impingement (FAI). Over time, FAI can lead to hip osteoarthritis (Ganz et al., 2003).

2.14 Research Equipment

2.14.1 OptiTrack Passive Motion Capture

The ability to quantify a participant's kinematics is essential to understanding the interaction between athletes and their equipment. OptiTrack motion capture systems are popular in biomechanics research and are becoming increasingly popular in this space (Nagymáté & M. Kiss, 2018). Passive motion capture systems use a network of cameras and reflective markers to identify an object's kinematics (van der Kruk & Reijne, 2018). Placing markers on important body landmarks allows a researcher to estimate body segment positions, and with multiple markers researchers can then estimate intersegment movements. When it comes to understanding athlete-equipment interaction, markers can be used to track equipment movement while a player is wearing it. This allows a researcher to compare the equipment movement to the athlete's body movement. In an ice hockey context this method was used by Frayne & Dickey (2017) to quantify leg pad movement around the leg. Additionally, the athlete's movement and joint angles can be quantified while wearing different equipment conditions, permitting biomechanical comparisons to be made between conditions.

The Vicon motion capture system has been considered the gold standard in this field; however, OptiTrack motion capture systems are proving to be as accurate and more cost effective. Carse et al., (2013) found up to a 2.2% difference between the OptiTrack system and two Vicon systems. In this study, it was acknowledged that only eight OptiTrack cameras were used compared to a 12 camera Vicon set up. An equal number of cameras could contribute to even higher success of the OptiTrack system (Carse et al., 2013). OptiTrack motion capture systems were reported as being reliable when assessing spinal curvature (ICC > 0.980) (Muyor et al., 2017).

There are few prior studies that use motion capture analysis in a hockey setting, and a smaller number of instances of those studies specifically using OptiTrack systems. Shell et al. (2017) used a Vicon motion capture system to observe kinematic differences between male and female during skating starts. Similarly, Renaud et al. (2017) used

Vicon motion capture to analyse differences between high and low caliber players during skating starts. When it comes to goaltenders, various studies have been performed which analysed equipment interaction, movement speed and joint biomechanics but have used Eagle motion capture systems (MotionAnalysis, CA, USA) (Frayne et al., 2015; Frayne & Dickey, 2017; Wijdicks et al., 2014). Additionally, Whiteside et al., (2015) observed goaltender kinematics while performing common goaltending movements using an Xsens inertial measurement unit system (Xsens Technologies, Netherlands).

2.14.2 Tekscan Pressure Sensors

Tekscan (MA, USA) pressure sensors allow a researcher to collect data regarding pressure between two surfaces. Tekscan produces various pressure monitoring systems that are commonly used for gait analysis, veterinary observation, and within the automotive industry (Assaf et al., 2019; Logan et al., 2021; Vakiel et al., 2020; Zenk et al., 2012). Tekscan pressure sensors read electrical resistance to measure contact pressure (Wettenschwiler et al., 2015). As pressure is applied to the sensor, intersections in a grid of conductive material (sensels) come together decreasing resistance. The accompanying scanning device identifies this change in resistance as pressure being applied to the sensor.

Prior studies highlight the importance of proper calibration and indicate that external factors can influence results. Moist or wet conditions can change the output of Tekscan pressure sensors. Also, pressure output readings decreased in humid or submerged conditions over time compared to a dry control (Jansson et al., 2013). It was concluded that Tekscan pressure sensors may not be reliable while testing human participants carrying load bearing vests because of the humidity that occurs during trials (Wettenschwiler et al., 2015). Since ice hockey goaltenders wear equipment, and perspire as they play (McCarthy et al., 2020; Palmer & Spriet, 2008), these concerns need to be considered.

Hockey related research has used Tekscan pressure sensors to quantify pressure. Plantar pressure at different skating velocities were measured with Tekscan pressure sensors (Turcotte, 2001). Similarly, ice hockey helmet research studies have used Tekscan pressure sensors to measure puck impact forces in skater helmets (Ouckama & Pearsall, 2011), as well as in goaltender helmets (Nur et al., 2015). Within this study, the Tekscan pressure sensors will be situated in the knee cradle and medial knee aspect of the pad as performed by Frayne & Dickey (2016) who used Tekscan pressure sensors on the medial knee stack to quantify drop impact forces. In their set-up, the player's knee pad will contact the pressure sensors rather than the skin surface of their knee. This barrier between the skin will reduce the moisture due to sweat around the sensor.

2.15 Scope of Research

This research is the result of collaboration with an industrial partner CCM Hockey. This thesis will focus on the fit, responsiveness and performance of leg pad conditions featuring stiff and flexible leg pad constructions along with a lace or elastic toe strap during the butterfly drop motion. It is acknowledged that indicators of safety, as well as biomechanical analysis during other movements are important; however, they fall outside of the scope of this thesis.

2.16 Research Question and Hypothesis

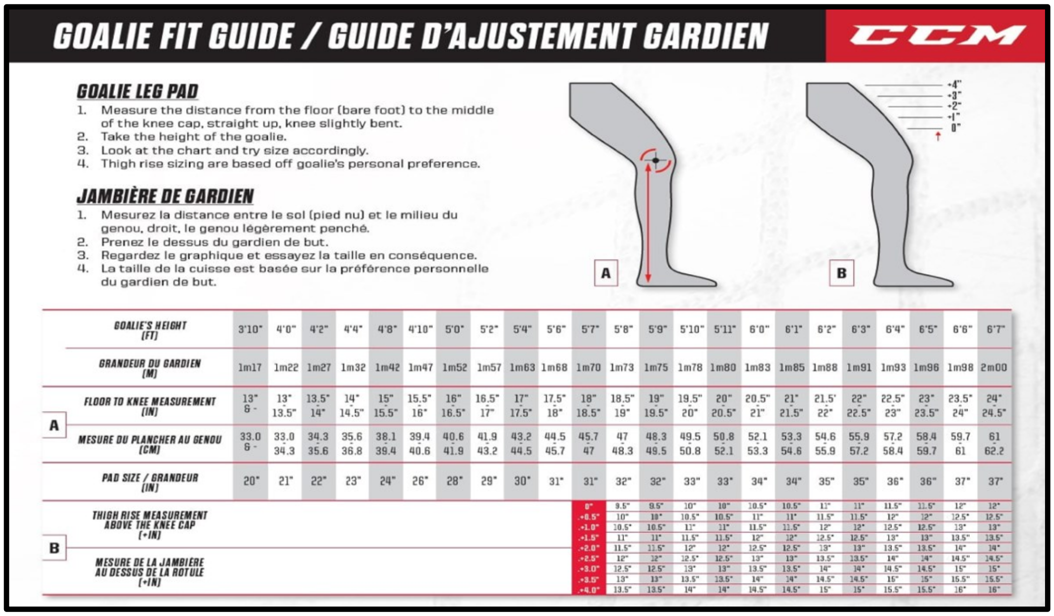
The equipment an athlete uses influences their ability to be successful in their sport; therefore, technologically advanced equipment is designed to help athletes reach their full potential. However, it is extremely important for biomechanical research to grow in parallel with equipment advancements to reduce knowledge gaps and improve the understanding of the athlete-equipment interaction (Stefanyshyn & Wannop, 2015). There is a lack of prior research in the field of ice hockey goaltender leg pad fit, responsiveness, and performance.

The primary aim of this study is to compare the performance, responsiveness and, fit between stiff and flexible leg pad constructions with lace or elastic toe straps. It is hypothesized that the stiff leg pad will have greater performance than the flexible leg pad but, the flexible leg pad will have superior fit, and responsiveness compared to the stiff leg pad. Secondarily, it is hypothesized that the elastic toe strap condition will have superior leg pad responsiveness compared to the lace toe strap, but not influence performance or fit.

Chapter 3: Methodology

3.1 Participants

This study included 17 healthy and experienced ice hockey goaltenders (15 male, 2 female) who competed at a level of Junior B or higher. Participants wore leg pads that were fit, based on a floor to knee measurement, in accordance with the manufacturer recommended guidelines (ca.ccmhockey.com: Figure 14). Participants currently affected by a hip or knee injury were excluded from the study for safety reasons.



GOALIE FIT GUIDE / GUIDE D'AJUSTEMENT GARDIEN

GOALIE LEG PAD

1. Measure the distance from the floor (bare foot) to the middle of the knee cap, straight up, knee slightly bent.
2. Take the height of the goalie.
3. Look at the chart and try size accordingly.
4. Thigh rise sizing are based off goalie's personal preference.

JAMBIÈRE DE GARDIEN

1. Mesurez la distance entre le sol (pied nu) et le milieu du genou, droit, le genou légèrement penché.
2. Prenez le dessus du gardien de but.
3. Regardez le graphique et essayez la taille en conséquence.
4. La taille de la cuisse est basée sur la préférence personnelle du gardien de but.

	GOALIE'S HEIGHT (FT)	3'10"	4'0"	4'2"	4'4"	4'8"	4'10"	5'0"	5'2"	5'4"	5'6"	5'7"	5'8"	5'9"	5'10"	5'11"	6'0"	6'1"	6'2"	6'3"	6'4"	6'5"	6'6"	6'7"
	GRANDEUR DU GARDIEN (M)	1m17	1m22	1m27	1m32	1m42	1m47	1m52	1m57	1m63	1m68	1m70	1m73	1m75	1m78	1m80	1m83	1m85	1m88	1m91	1m93	1m96	1m98	2m00
A	FLOOR TO KNEE MEASUREMENT (IN)	13" 6 -	13" - 13.5"	13.5" - 14"	14" - 14.5"	15" - 15.5"	15.5" - 16"	16" - 16.5"	16.5" - 17"	17" - 17.5"	17.5" - 18"	18" - 18.5"	18.5" - 19"	19" - 19.5"	19.5" - 20"	20" - 20.5"	20.5" - 21"	21" - 21.5"	21.5' - 22"	22" - 22.5"	22.5" - 23"	23" - 23.5"	23.5" - 24"	24" - 24.5"
	MESURE DU PLANCHER AU GENOU (CM)	33.0 6 -	33.0 - 34.3	34.3 - 35.6	35.6 - 36.8	38.1 - 39.4	39.4 - 40.6	40.6 - 41.9	41.9 - 43.2	43.2 - 44.5	44.5 - 45.7	45.7 - 47	47 - 48.3	48.3 - 49.5	49.5 - 50.8	50.8 - 52.1	52.1 - 53.3	53.3 - 54.6	54.6 - 55.9	55.9 - 57.2	57.2 - 58.4	58.4 - 59.7	59.7 - 61	61 - 62.2
	PAD SIZE / GRANDEUR (IN)	20"	21"	22"	23"	24"	26"	28"	29"	30"	31"	31"	32"	32"	33"	33"	34"	34"	35"	35"	36"	36"	37"	37"
B	THIGH RISE MEASUREMENT ABOVE THE KNEE CAP (+IN)											0"	9.5"	9.5"	10"	10"	10.5"	10.5"	11"	11"	11.5"	11.5"	12"	12"
												+0.5"	10"	10"	10.5"	10.5"	11"	11"	11.5"	11.5"	12"	12"	12.5"	12.5"
												+1.0"	10.5"	10.5"	11"	11"	11.5"	11.5"	12"	12"	12.5"	12.5"	13"	13"
												+1.5"	11"	11"	11.5"	11.5"	12"	12"	12.5"	12.5"	13"	13"	13.5"	13.5"
												+2.0"	11.5"	11.5"	12"	12"	12.5"	12.5"	13"	13"	13.5"	13.5"	14"	14"
	MESURE DE LA JAMBIÈRE AU DESSUS DE LA ROTULE (+IN)											+2.5"	12"	12"	12.5"	12.5"	13"	13"	13.5"	13.5"	14"	14"	14.5"	14.5"
												+3.0"	12.5"	12.5"	13"	13"	13.5"	13.5"	14"	14"	14.5"	14.5"	15"	15"
												+3.5"	13"	13"	13.5"	13.5"	14"	14"	14.5"	14.5"	15"	15"	15.5"	15.5"
												+4.0"	13.5"	13.5"	14"	14"	14.5"	14.5"	15"	15"	15.5"	15.5"	16"	16"

Figure 14. CCM hockey goaltender equipment fit guide used to choose leg pad size during condition trials.

Participants provided written informed consent to participate in the study and completed a Health History Questionnaire (Appendix A) to confirm study eligibility. The experimental design and protocols were approved by the Dalhousie Health Sciences Research Ethics Board (REB file#: 2020-5131; Appendix C). This research was conducted at Dalhousie University's Biomechanical Ergonomics and Neuroscience Laboratory (BENlab) (2661 South St. Halifax, NS. Canada).

3.2 Hardware

A 14-camera OptiTrack passive motion capture (OptiTrack, Natural Point, Oregon, USA) configuration and associated reflective markers were used to obtain kinematic data of the participant and their equipment. The testing leg pads had a Velcro (loop) anterior surface for adhering four rigid body marker sets (hook Velcro) at the thigh, knee, shin, and boot of the pad (Figure 15). On the participant, markers were place on the hips at the left and right anterior superior iliac spine and posterior superior iliac spine, rigid bodies were attached at the lateral thigh, and posterior shank using elastic straps. Motion capture data was sampled at 60Hz.

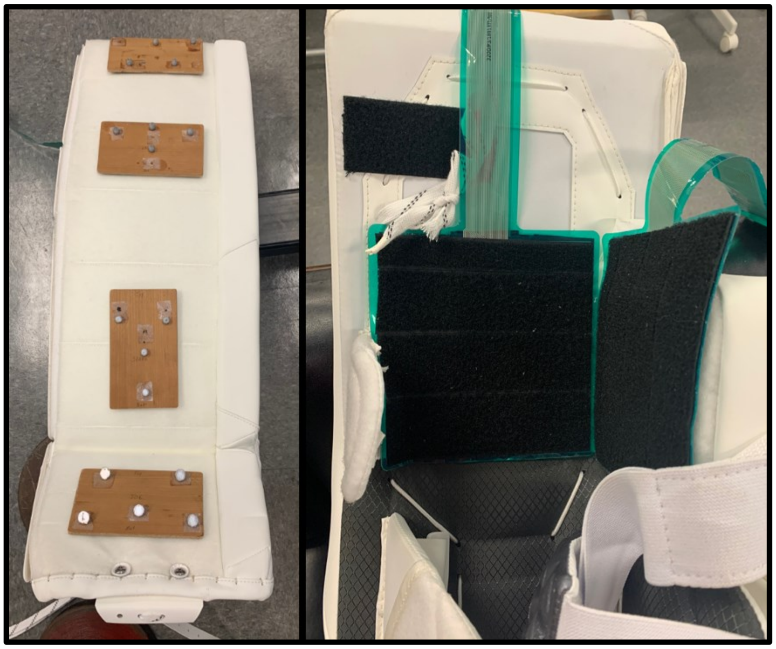


Figure 15. Left: Goaltender leg pad with rigid body marker sets adhered at the boot, shin, knee, and thigh of the pad. Right: Goaltender leg pad posterior view showing location of Tekscan pressure sensors.

Two Tekscan 3200E pressure sensors (Tekscan, Massachusetts, USA) were attached to the anterior knee padding and medial knee stack (Figure 16) using Velcro, to obtain knee pressure location data. All Tekscan sensors were sampled at 840Hz. Two Tekscan attachment cuffs (connecting the sensors to the Tekscan hardware) were also secured to the pad to minimize vibration of the Tekscan hardware during goaltender movements. Cables were connected to the attachment cuffs, then looped through an elastic strap on the participant's waist and taped to the crossbar of the net to minimize the risk of cable lacerations from skates. Tekscan sensors were calibrated using a Mark 10 force gauge (Mark-10 Corp., New York, USA) prior to data collection.

Figure 16. Simulated overlay of Tekscan pressure sensor output on medial knee stack.

3.3 Software

Motion capture data was collected and processed using Motive motion analysis software (Natural Point, Oregon, USA). This program permitted camera set up, calibration, and real time data collection of the reflective markers. Motive was also used for post-trial processing which involves labeling the reflective markers and rigid bodies for each trial, then exporting the tracked data to Excel (Microsoft. Washington, USA). Specific columns were extracted (eg. Y marker position) from the motion capture data

(Excel file) and used in custom MATLAB programs to determine performance and responsiveness outcome variables.

Tekscan pressure sensor data was collected using Tekscan Conformat software 7.10 (Tekscan; Massachusetts, USA) to configure data collection settings and collect knee pressure data during trials. Data from this software was also exported to Excel for further analysis. In Excel, data was trimmed to exclude unnecessary data and a custom MATLAB program was used to determine fit outcomes.

3.4 Synthetic Ice Surface

Trials were performed on a 9’x12’ foot synthetic ice surface. The synthetic surface had a regulation NHL size crease inlay. Attached to the surface with bolt-fastened aluminum pegs was a regulation size goal net that had the mesh backing removed to improve the camera views of the posterior side of the goaltender and equipment (Figure 16). Related studies observing player shooting (Michaud-Paquette et al., 2009) and goaltender biomechanics (Frayne & Dickey, 2017) have similarly used synthetic ice materials.

Figure 17. Synthetic ice with regulation crease and net with no mesh within the BENlab.

3.5 Leg Pad Conditions

This study quantified leg pad fit, responsiveness and performance between three leg pad conditions that differed in flexibility profiles and toe strap type. The three leg pad conditions were:

Condition 1 – *Stiff leg pad with elastic toe strap*

Condition 2 – *Stiff leg pad with skate lace toe strap*

Condition 3 – *Flexible leg pad with skate lace toe strap*

The stiff leg pads were manufactured with a detachable toe strap area to allow for the interchanging of toe strap conditions from skate lace toe strap to elastic toe strap and vice versa. To decrease the amount of friction between the leg pad and the synthetic ice surface, customized medial sliders made from high density polyethylene were secured to the medial side of the pad using adhesive hook Velcro to improve sliding (Figure 17).

Figure 18. Medial side of a goaltender leg pad with customized polyethylene sliders adhered via hook Velcro to help the pad slide along the synthetic ice surface.

3.6 Experimental Protocol

Participants were introduced to the testing area and equipment, then given time to ask questions prior to providing informed consent. Height, weight, and knee – to – floor height anthropometrics were measured and recorded. Participants then changed into tight fitting clothing that was worn underneath their goaltending equipment. During testing trials, the ice hockey goaltender leg pads would occlude markers located on the goaltender’s knee and ankle. Therefore, to assess the leg pad’s movement about the participant’s tibia, a calibration trial was performed prior to participants dressing in the goaltender equipment to determine the relationship between the lower leg anatomical landmarks and the raised calf rigid body.

Figure 19. Left: Anterior view of calibration trial marker setup. Middle: Posterior calf rigid body. Right: During the pad condition trial the calf rigid and upper thigh rigid bodies as well as skate and hip individual markers remain on the participant.

The calibration trial consisted of using four reflective markers located on the participant's left leg: medial and lateral malleolus, and medial and lateral tibial plateau along with a rigid body on the calf that would remain attached to the goaltender throughout testing (Figure 18). Upon completion of the calibration trial, the reflective markers around the knee and ankle were removed so that participants could put on the testing leg pads.

Goaltenders proceeded through testing trials in each of the three leg pad conditions in a randomized order. Pad order was randomized with a three condition block design (Kim & Shin, 2014). Trials in each pad condition lasted approximately 15-20 minutes. Goaltenders performed four repetitions of four goaltending movements: a butterfly drop and recovery, a reverse vertical horizontal (RVH) post-to-post, a butterfly drop and slide, a lateral t-push (Figure 19) in an order randomised in Microsoft Excel (Microsoft, WA, USA). On the researcher's cue, goaltenders performed one repetition of the instructed movement at maximal effort. Following the movement

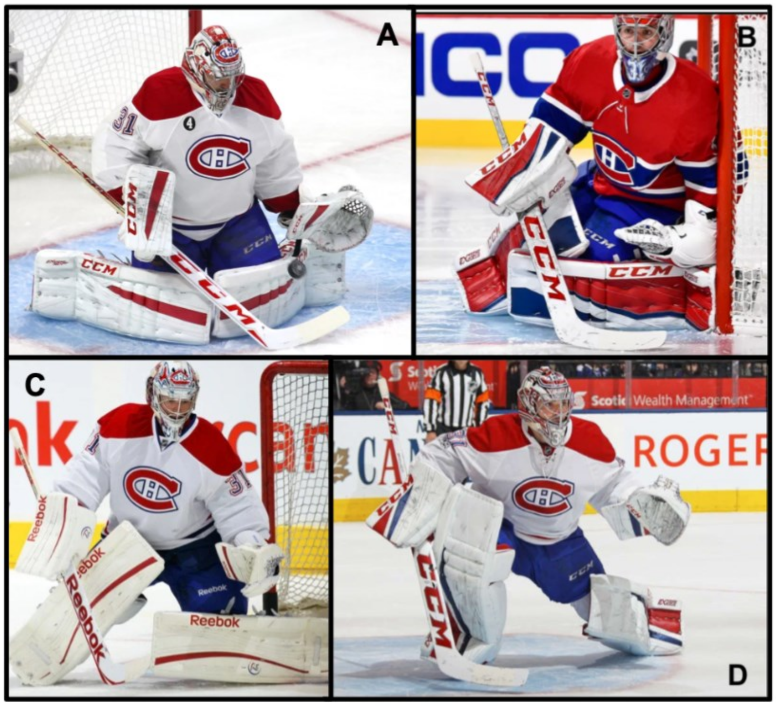


Figure 20. Depiction of the movements that participants performed during trials. (A) Butterfly, (B) RVH, (C) Backside edge push, (D) T-Push.

and associated data acquisition, participants had approximately 30 seconds to prepare for the next movement.

As mentioned prior, this thesis will focus specifically on the butterfly drop motion. Therefore, the data used within this thesis were obtained from the butterfly drop and recovery movement, and the butterfly drop push left slide movement.

3.7 Data Analysis

3.7.1 Coding programs

Trimmed excel files were imported to MATLAB for further analysis. Performance and responsiveness data were filtered using a fourth order low-pass Butterworth filter with a 6Hz frequency cut-off (Frayne & Dickey, 2017; Winter, 2009).

Performance was defined as the peak downward pad movement velocity during a butterfly drop (Frayne & Dickey, 2017). Leg pad vertical drop velocity was determined by calculating the derivative of the leg pad's superior lateral thigh marker positional data. Velocity was calculated using the three-point central difference method. The peak vertical drop velocity value was then determined during the butterfly drop phase (Figure 20).

Leg pad responsiveness was defined as the movement time difference between a participant's shank and the leg pad at the initiation of the butterfly drop. Vertical position data from the pad shin and the raised calf board from each butterfly drop trial were used to estimate responsiveness. Using the calibrated relationship between the raised calf board rigid body and the participant's shank, the position of the participant's shank was calculated. Then the vertical position of the most inferior marker on the pad's shin and the middle of the participant's shank was used to calculate the vertical velocity of each using the central difference method.

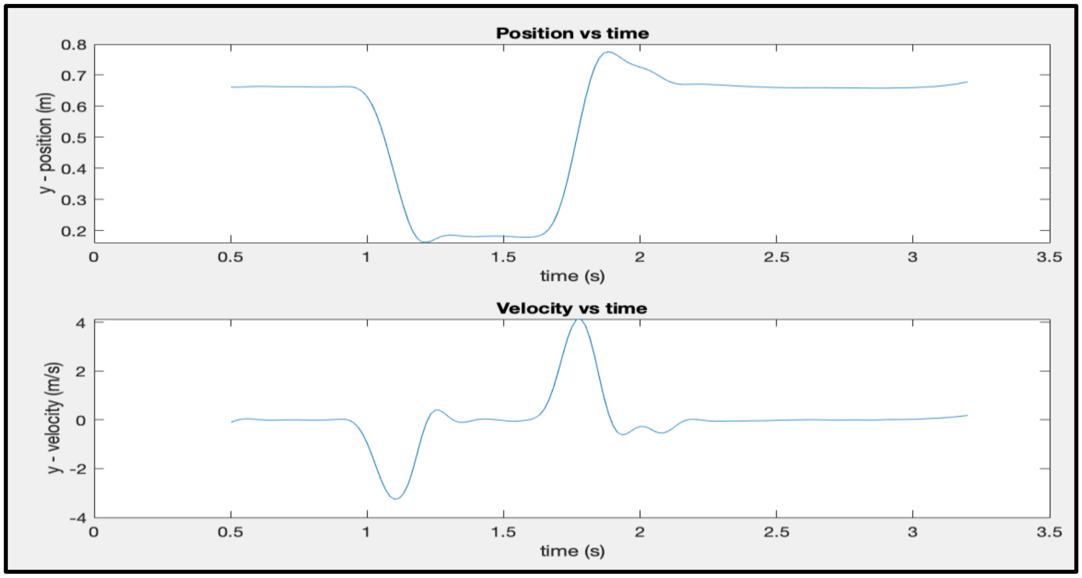


Figure 21. Resulting graphs from performance data. The top graph depicts a thigh marker's vertical (y-axis) position over time. The bottom graph depicts the same marker's velocity over time. Peak drop velocity is the minimal point on the velocity vs. time graph at approximately 1.15s. The positive peak velocity represents the upward velocity when the participant is recovering to their standing position.

The initiation of movement was determined as the time when each of the leg pad and participant's shank crossed a downward velocity threshold. This threshold was defined as 3 standard deviations below the mean pre-movement prepared stance (ie. not moving) velocity of the shank across all participants' butterfly drop and recovery trials (n=199). The time difference between when the leg pad and the shank crossed this threshold was measured as leg pad responsiveness.

Fit was defined as the distance of knee CoP from the middle of the knee stack at ice impact. Anterior-posterior fit was a measure of the CoP location, in relation to the middle of the knee stack, along the anterior-posterior axis. Superior-inferior fit was a measure of knee CoP, from the middle of the knee stack, along the superior-inferior axis. Tekscan Conformat software gave a CoP location relative to the pressure sensor on the knee stack, and full sensor pressure output during movements. Tekscan data was imported into MATLAB to determine the butterfly drop impact time. Impact time was identified by a large spike in total sensor pressure. This impact time was cross referenced with the CoP location provided from the Tekscan Conformat software to identify the knee superior-inferior and anterior-posterior CoP locations at butterfly drop impact.

3.7.2 Excluded data

Performance data for one participant was excluded. For this participant, the markers on the superior medial area of the leg pad were consistently being occluded by the participant's upper extremities. The problem was consistent across all three leg pad conditions making it difficult to determine an accurate butterfly drop. Therefore, performance calculations feature the results from 16 participants. Fit and responsiveness outputs were calculated from trials of all 17 participants.

3.7.3 Statistical Analysis

Mean participant outcomes were achieved by averaging the four trials, for each specific movement (eg. Butterfly movements), in each condition. If participants had a trial error and the data was impacted, then movement/condition outcomes were averaged from the remaining good trials. Therefore, all participants had an average outcome score for each goaltender movement/leg pad condition (except participant one - performance outcomes).

Data for each outcome variable was tested for normality using a Shapiro-Wilk test. Performance, and fit data were normally distributed (p>.05) but responsiveness data was not normally distributed (p<.05). Normal data was tested for sphericity using a Mauchly's test.

For performance, a 1-way repeated measures ANOVA was used to compare peak butterfly drop velocity in each leg pad condition. Fit outcomes were broken into superior-inferior and anterior-posterior fit. For each, a 1-way repeated measures ANOVA was used to compare distance from the midline in each leg pad condition. If significant main effects were found during the repeated measures ANOVAs posthoc pairwise t-tests using the modified Bonferroni correction (Moss, 2009) were conducted along with Cohan's d for estimates of effect size (Sullivan & Feinn, 2012). Since responsiveness data was not normally distributed, a Friedman's test was conducted.

Chapter 4: Results

4.1 Performance

During butterfly movements, participants reached an average peak drop velocity of 2.76 ± 0.43 m/s (mean ± 1 standard deviation). The stiff-lace leg pad condition had the fastest average velocity (2.78 ± 0.51 m/s) of all the conditions (Table 1). However, there was no significant main effect of leg pad condition on performance ($F_{2,30} = 0.575$, $p > .05$, $n_p^2 = 0.037$) (Figure 21).

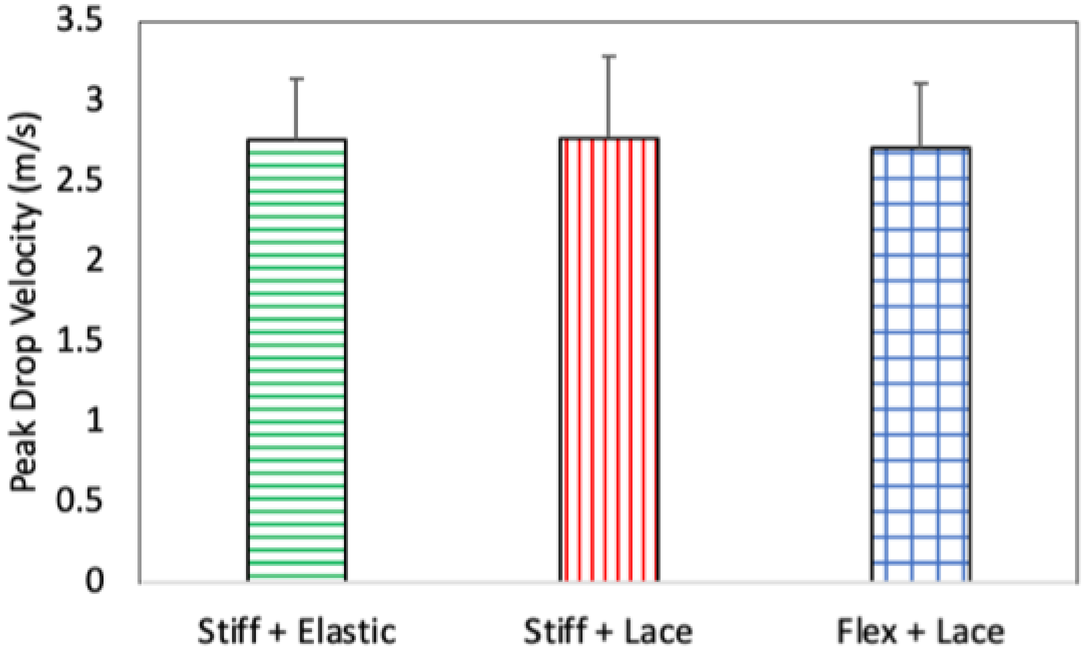


Figure 22. Bar graph representation of leg pad performance in each of the leg pad + toe strap conditions. Error bars representing 1 standard deviation above or below the group mean.

4.2 Responsiveness

At the initiation of the butterfly drop, all leg pad conditions trailed behind the goaltenders' shank movement by an average of 0.021 ± 0.020 s (Figure 22). There was no significant main effect of leg pad condition on responsiveness ($X^2 = 1.182$, $p > .05$).

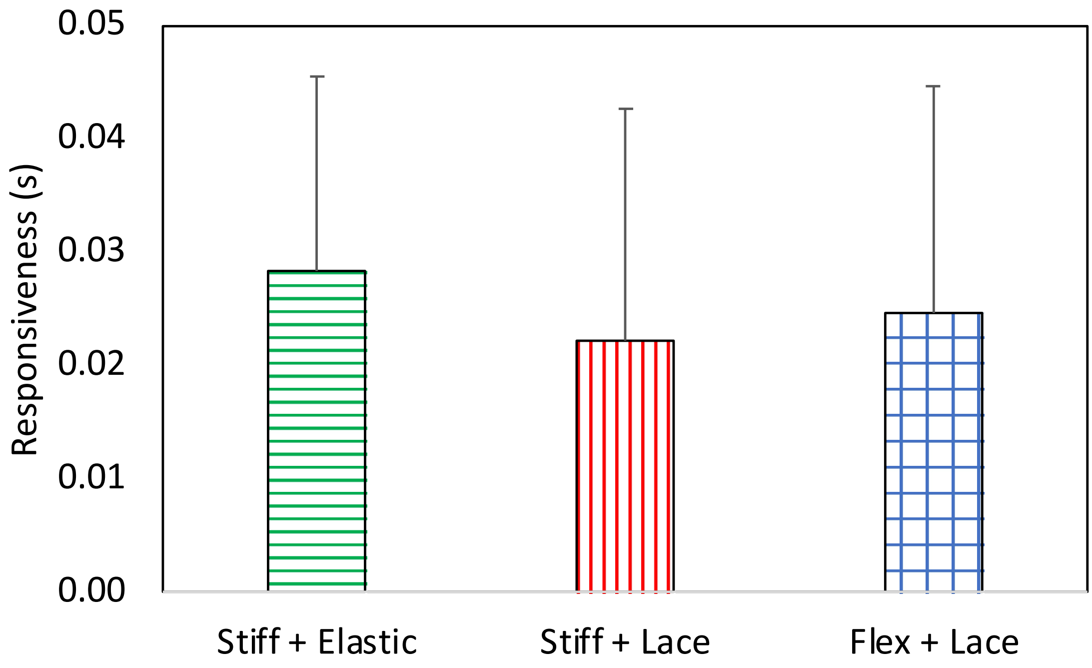


Figure 23. Bar graph representation of leg pad responsiveness in each of the leg pad + toe strap conditions. Error bars representing 1 standard deviation above or below the group mean.

4.3 Fit

Across all trials, participants landed 1.07 ± 1.24 cm anterior and 4.01 ± 0.82 cm inferior to the midpoint of the knee stack. In all leg pad conditions, participants landed below and anterior to the midpoint of the knee stack (Figure 23). There was no significant difference in anterior-posterior fit between leg pad conditions

($F_{2,32} = 0.594$, $p > .05$, $n_p^2 = 0.036$). There was a significant main effect of leg pad condition on superior-inferior fit ($F_{2,32} = 4.930$, $p < .05$, $n_p^2 = 0.236$). Paired comparisons revealed no significant differences between conditions after adjusting for multiple comparison bias (Table 1); however, medium effects were identified between stiff vs flexible leg pad conditions.

Table 1. Superior – Inferior fit paired t-test results with modified Bonferroni alpha correction value and Cohen's d.

First pad condition	Second pad condition	Mean Difference (cm)	P-Value	Modified Bonferroni Alpha	Cohen's d effect size
Stiff + Elastic	Stiff + Lace	0.017	.888	.05	0.035
Stiff + Elastic	Flexible + Lace	0.465	.033	.025	0.566
Stiff + Lace	Flexible + Lace	0.482	.024	.016	0.605

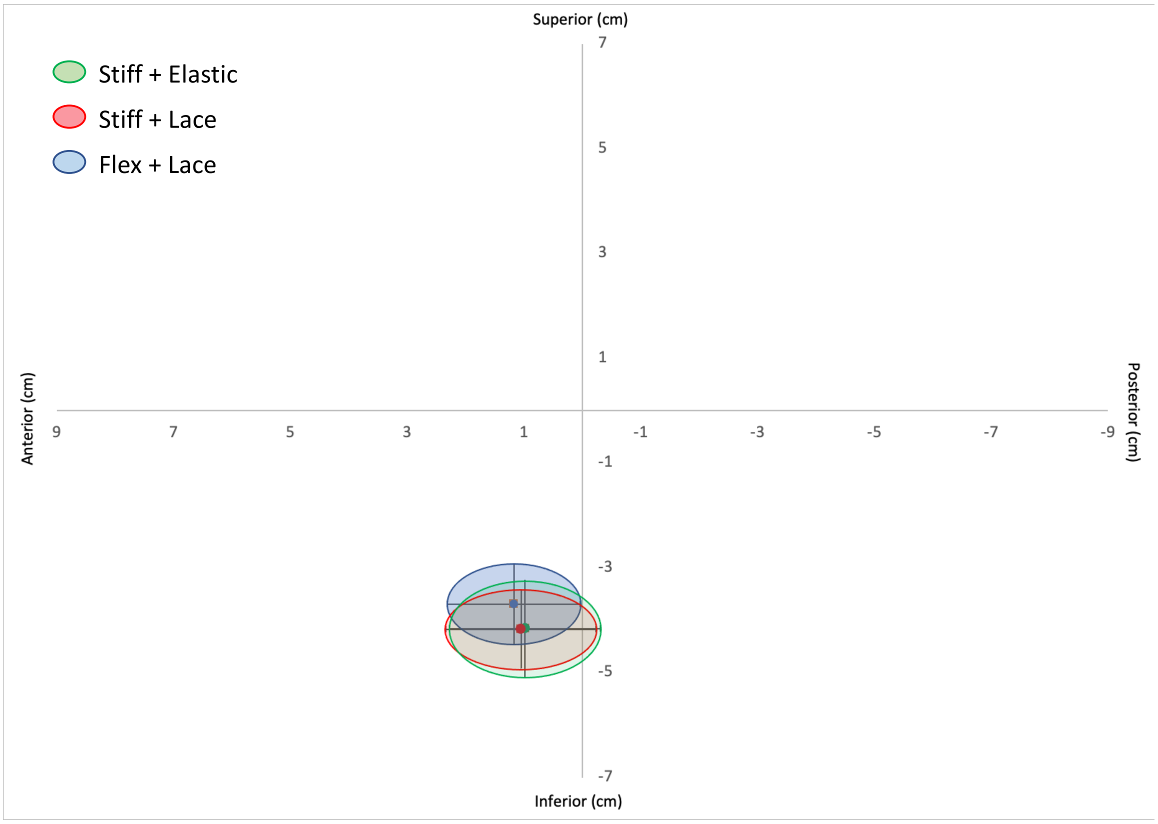


Figure 24. Butterfly knee drop center of pressure location on the pad's knee stack. Axes are arranged so that the graph visually represents a shape similar to that of the knee stack. Error bars represent 1 standard deviation (SD) from the mean both for both anterior-posterior and superior-inferior fit metrics and are connected in with an ellipse shape.

4.4 Results Summary

Table 2. Summary table of performance, responsiveness, and fit results in each leg pad condition.

Metric		Stiff + Elastic	Stiff + Lace	Flexible + Lace	Group Mean
Performance N = 16	Peak Butterfly Drop Velocity (m/s)	2.77 ± 0.38	2.78 ± 0.51	2.72 ± 0.40	2.76 ± 0.43
Responsiveness N = 17	Pad – Leg Movement Time Difference (s)	0.022 ± 0.019	0.019 ± 0.021	0.022± 0.021	0.021 ± 0.020
Fit N = 17	Superior-Inferior Knee Impact Location (cm)*	-4.16 ± 0.93	-4.17 ± 0.75	-3.69 ± 0.77	-4.00 ± 0.82
	Anterior-Posterior Knee Impact Location (cm)**	0.98 ± 1.29	1.05 ± 1.29	1.17 ± 1.14	1.07 ± 1.24

* Negative value represents impact inferior to the midpoint of the knee stack.

** Positive value indicates impact anterior to the midpoint of the knee stack.

Chapter 5: Discussion

The purpose of this research was to compare the performance, responsiveness, and fit of three ice hockey goaltender leg pad conditions during the butterfly movement. It was hypothesized that the stiff leg pad would have greater performance outcomes, and the flexible leg pad would have superior fit, and responsiveness outcomes. Additionally, it was hypothesized that the elastic toe strap would result in greater responsiveness but not affect fit or performance. The data from this study partially supports the first and second hypotheses. There were no significant differences between all three leg pad and toe strap conditions in terms of performance, responsiveness, or anterior-posterior fit. However, there was a significant main effect of pad condition on superior-inferior fit. While there was no significant pairwise differences between the individual leg pad conditions, butterfly drop CoP was closer to the middle of the knee stack in the flexible pad than the stiff pad conditions.

5.1 Performance

Goaltender performance was defined as the peak vertical drop velocity of the leg pad during the butterfly drop movement. In elite ice hockey, players can shoot pucks over 160 km/h (Marrazza, 2017). Therefore, it is imperative that goaltenders get into their save positions quickly, giving them a better chance of stopping the shot. Previous research suggests that leg pad construction (stiff versus flexible leg pad) may contribute to a goaltender’s ability to move rapidly and stop oncoming shots (Frayne & Dickey, 2017). However, in this study there was no significant difference in butterfly drop velocity performance between the three leg pad conditions. Therefore, the hypothesis that stiff leg pads would have greater performance than flexible leg pads was rejected. All three leg pad conditions had similar performance scores with the stiff leg pad constructions (elastic and lace) having mean velocities separated by 0.01 m/s (Stiff lace = 2.78 ± 0.51, Stiff elastic = 2.77 ± 0.38), while the flexible lace leg pad (flexible lace = 2.72 ± 0.40) was only slower than the stiff lace condition by 0.05 m/s.

Current leg pads must conform to regulations set by the National Hockey League (NHL, 2020). To maximize goaltender effectiveness, these leg pads are being made to the maximum limit of the regulations (Frayne & Dickey, 2016) despite their differences in construction. Also, advancements in equipment development may result in desirable leg pad construction, that will then be used in the future generations of other leg pad models (ie. a large equipment advancement in the stiff leg pad model may then be applied to the flexible leg pad model). The combination of building equipment to the maximum regulation and using desirable leg pad construction in various leg pad models results in the leg pad models becoming similar. These phenomena may partially explain why there were no performance differences observed in this study.

An example of pad similarity can be seen in the boot region of current leg pad constructions. Previously, stiff leg pads were more rigid throughout the entire pad; however, these stiff leg pads were slower in butterfly drop performance compared to the flexible leg pads (Frayne & Dickey, 2017). Now, stiff leg pads, including those used in this study, maintain their rigid construction through the thigh and shin of the pad but have a more flexible boot and shape like that of the flexible leg pad. The similarities in flex profile within the boot region of the leg pads may also have resulted in the stiff and flexible leg pads performing similarly.

Previous research has reported that goaltenders wearing leg pads of varying widths and wear characteristics take between 0.14 and 0.47 s to drop into the butterfly position (Wijdicks et al., 2014) but did not report peak drop velocities. Frayne & Dickey (2017) reported downward peak velocity of 2.98 ± 0.51 m/s in their stiff + wide leg channel pad condition. The current research project had a comparable participant population to Frayne & Dickey (2017); however, there remained a performance difference of 0.22m/s between these two studies. This difference could be the result of marker location differences, the addition of two Tekscan sensors and attachment cuffs within the current study or an effect of recent pad construction changes.

While peak drop velocity was not significantly different in different leg pad conditions, 9 out of 16 participants (~56 %) were faster in the stiff lace pad condition than in the flexible lace pad condition. Four participants (25%) were faster in the flexible lace condition and three participants had equal velocities. Out of 16 participants, six were faster in the stiff elastic condition (37.5%) and eight were faster in the stiff lace pad condition (50%). On average, the stiff elastic pad condition was just 0.01 m/s slower than the stiff lace pad condition highlighting that toe strap differences had minimal effect on performance (Table 2).

In ice hockey the difference between stopping a shot and giving up a goal could come down to a few centimeters of movement. To give context, if drop velocity was assumed to be consistent throughout the movement, and the movement distance was observed over a consistent interval, the flex lace condition pad (2.72 m/s) would be approximately 2 cm from the ice at the same time the stiff lace condition pad (2.79 m/s) made contact with the ice surface. An ice hockey puck is just 2.54 cm thick (NHL, 2020) so this small difference in performance could possibly affect goaltending effectiveness in a game setting.

5.2 Responsiveness

Responsiveness was quantified as the time difference between the initiation of the goaltender's leg movement and their leg pad. This was completed by having both the leg and the leg pad exceed a common velocity threshold. On average, all leg pad conditions trailed behind the leg by 0.021 ± 0.020 seconds (Table 2), including the elastic toe strap condition which was hypothesized to have superior responsiveness. Therefore, the hypotheses that the flexible leg pad and the elastic toe strap conditions would have superior responsiveness was rejected. This indicates that the all the leg pad conditions are highly responsive to goaltender downward butterfly movements.

There are two main factors that account for modern leg pad responsiveness. The first is that leg pads are often equipped with elastic attachment strapping that securely attaches the pad to the lower leg (Figure 8). These strapping systems are likely responsible for the very small amount of time that the pad trailed behind the shank in this study. Older leg pads featured traditional leather straps that required slack between the goaltender's leg and the leg pad to permit goaltender movement. However, with modern elastic strapping, this slack is removed, and goaltenders are still able to move around freely without much resistance from the leg pads. Therefore, the modern elastic strapping system may play an integral role in leg pad responsiveness during the butterfly movement. The second factor resulting in good leg pad responsiveness is the stiff medial knee stack. As goaltenders drop into the butterfly position, their knees move toward the anterior knee cradle and medially into the knee stack (Frayne & Dickey, 2017). Therefore, as the goaltender's knee pushes forward and medially it contacts the anterior, then medial surface of the knee cradle driving the leg pad toward the ice surface and preventing the pad from trailing the leg.

To the best of the authors knowledge, this research project was the first attempt to track goaltender equipment responsiveness. Since responsiveness outcomes were so small, this metric was limited by sampling rate of the motion capture data. Although, the average responsiveness values exceeded that of the minimum time period between samples (0.017 seconds), a higher sampling frequency may have identified small responsiveness differences between the leg pad conditions.

A highly responsive pad is necessary when dropping into the butterfly position as an increased delay in leg pad responsiveness could lead to increased time for the pad to reach the ice, improper landing, or other detriments to success. However, once a goaltender is in the butterfly position and transitioning/sliding from side to side, it is imperative that the leg pads remain flat along the ice surface to be effective against low shots. In this situation, if a leg pad is over responsive, contact with the ice may be lost too quickly, and the goaltender could be more susceptible to low shots. Therefore, this creates a manufacturing challenge as leg pad responsiveness should be different depending on if a goaltender is dropping into the butterfly (desire a high responsiveness) or transitioning between butterfly positions (desire a medium - low responsiveness).

5.3 Fit

As a goaltender drops into the butterfly position, their knee lands on medial knee stack of the leg pad. This allows the anterior surface of the pad to rotate externally around their shank and remain facing forwards while they are in the butterfly save position. Fit was quantified as the participant's knee CoP on the knee stack in both anterior-posterior and superior-inferior directions when the participant lands on the ice during a butterfly drop movement. Anterior-posterior fit was not significantly different across leg pad conditions. There was a significant main effect of pad condition on superior-inferior fit, but pairwise comparisons were not significant despite moderate effect sizes between the stiff leg pad conditions and the flexible leg pad condition. Therefore, the hypothesis that the flexible leg pad with lace strap condition would have a superior anterior-posterior and superior-inferior fit was rejected. Knee impact CoP for the stiff leg pad conditions was similar; therefore, we accept the hypothesis that toe strap condition did not have a significant impact on leg pad fit.

Anterior-posterior fit values for all leg pad conditions were within 0.2 cm of each other and an average of 1.07 ± 1.24 cm from the midline. This measure was closer to the midline and less variable between conditions than superior-inferior fit. This is likely due to the posterior elastic strapping system that is consistent across all leg pad conditions and ensures that the leg pad stays close to the knee during movement.

The leg pad medial knee stack is designed to provide a landing area for the goaltender while they drop into butterfly positions. Goaltenders drop into the butterfly position 32 times during a game (Bell et al., 2008) and 300 times during a practice (Epstein et al., 2013). With repetition based injuries being prominent among goaltenders (Epstein et al., 2013; Wörner et al., 2019), it is necessary to understand if the goaltender's knees are landing in a safe location on the leg pad knee stack.

The flexible pad with lace toe strap would be the most beneficial led pad conditions for player safety. Knee CoP impact location was closer to the superior-inferior midline in the flexible lace pad condition compared to both stiff lace, and stiff elastic leg pad conditions. On average, in the flexible leg pad condition, participants landed nearly 0.5 cm closer to the midline of the knee stack (Table 2) than both stiff leg pad conditions. Landing further from the midline of the knee stack is a safety concern because there may be at risk of missing the stack during butterfly drops or sliding off the knee stack when moving into the butterfly position.

In terms of goaltender effectiveness, balance, and stability are common topics of discussion among ice hockey goaltenders and equipment manufacturers. Goaltenders are frequently in kneeling positions such as the butterfly, making it imperative that a goaltender's knee is positioned on the leg pad knee stack to improve their balance. A lack of balance could lead to inconsistent movements, an inability to make saves, or injury. The results of this study suggest that the flexible leg pad condition would again be the most beneficial for goaltenders because it places a goaltender's knee closer to the center. However, future research is necessary to determine if landing centrally on the knee stack is the most beneficial to a goaltender's balance.

The most important observation of the superior-inferior fit results is that on average all leg pad conditions had an impact location 4.00 ± 0.82 cm inferior to the midpoint. The knee stack is 14 cm tall meaning that in all three leg pad conditions knee impact occurred within the bottom quarter of the knee stack. The low CoP location may result in portions of the goaltender's knee guards being unsupported by the knee stack (ie. hanging off the bottom of the knee stack), which is a safety and performance concern. Goaltender's landing low on the knee stack, may cause a bending moment at the knee stack impairing performance by decreasing goaltender balance.

Each participant was fit into the leg pads based on the manufacturer sizing guidelines (Figure 14). These results suggest that the sizing charts may be incorrect and need to be updated so that goaltenders are wearing smaller leg pads that would result in the knee landing more centrally on the knee stack. However, goaltenders typically prefer larger equipment to help cover more space in their net, so encouraging them to wear a smaller leg pad would be poorly received. Alternatively, moving the knee stack downwards on the medial side of the leg pad, and adding pad height to the thigh region, could help to improve where the knee impacts the knee stack without sacrificing goal net coverage.

5.4 Research Limitations

This research took place on a synthetic ice surface. There could be differences between how a goaltender moves on synthetic ice compared to a real ice surface.

However, this research project only focused on the butterfly drop and landing, not sliding or skating so any friction effects from the synthetic ice surface should be minimized.

When quantifying performance, this study only accounted for the vertical aspect of the drop to the ice. However, in the interest of performance, the most important factor was how quickly the pad could reach the ice surface. For that reason, the pad's vertical velocity was the most important aspect to measure. Also, as mentioned in section 5.2, the responsiveness measurement used vertical velocity to determine when the goaltender's leg and leg pad exceeded the initiation velocity threshold. The 60Hz sampling rate and 6Hz low pass Butterworth filter used to collect and filter the data for this study were used based on butterfly drop performance results and methods used in prior research (Frayne & Dickey, 2016). Future research investigating leg pad responsiveness should consider a higher sampling rate to improve the resolution of the outcome. This would also permit a higher filter cut off, if needed to detect smaller equipment response values.

Participants in this study performed a total of 48 movements. This could lead to fatigue as they progressed through the trials. However, each movement lasts only a few seconds, and they are spread out over approximately 1-1.5 hours allowing for ample recovery time. Goaltenders were provided with water, and informed that they could take a rest as desired. The order that the leg pad conditions were presented to the goaltender was randomized to reduce effect of fatigue.

It was possible that goaltenders were familiar with one specific leg pad compared to another due to the equipment they currently wear for competition. However, goaltenders were given time in all setup conditions in the lab to familiarize themselves and practice movements before starting the trials.

5.5 Future Research

The rate of equipment development can often surpass biomechanical research that studies the interaction between the equipment and the athlete (Stefanyshyn & Wannop, 2015). Moving forward it is important to remain up to date on ice hockey goaltender equipment biomechanics as equipment progresses and changes over time. Understanding the effect of new leg pad features or constructions will help inform goaltenders and manufacturers about how these changes affect goaltender safety and performance and assist in future equipment developments.

It would be beneficial for future research to observe knee CoP locations in other goaltender movements or positions beyond the butterfly to better understand how to improve leg pad fit. Understanding where knee CoP is located on the knee stack during various goaltender movements could inform if the current location of the knee stack should be adjusted.

Future research should also aim to identify what makes a balanced/stable ice hockey goaltender leg pad. Since ice hockey is a dynamic sport, simply observing the static balance of a leg pad on its own is not adequate; therefore, identifying how a goaltender interacts with the leg pad and maintains balance throughout the butterfly movement is important. Specifically, a study should be conducted to determine how landing on different areas of the knee stack may affect a goaltender's balance when in the butterfly position. For example, does landing further away from the midpoint of the knee stack improve or decrease a goaltender's balance.

Goaltenders wear knee guards between their knees and leg pads. There are many available models, features, and personal alterations to these knee guards. Factors such as knee guard material, shape and thickness influence the athlete's interaction with the medial knee stack thus factoring into their ice contact and balance when performing a butterfly movement. It would be beneficial to research differences between models of knee guards to get a better understanding of how to optimize this piece of equipment.

5.6 Conclusion

This study adds to the limited amount of research on ice hockey goaltender equipment biomechanics. The performance data from this study builds upon Frayne & Dickey (2017) by updating the constructions of leg pads used to reflect current constructions. These current leg pad and toe strap conditions resulted in similar outcomes of performance, responsiveness, and anterior-posterior fit. There were medium effect sizes when comparing the superior-inferior fit in the stiff leg pad conditions to the flexible leg pad condition, suggesting that goaltenders are landing closer to the middle of the knee stack in the flexible condition: however, all leg pad conditions had knee CoP impact locations within the bottom 25% of the knee stack. The reported fit outcomes are important for manufacturers because participants are systematically landing below the midpoint of the knee stack in both flexible and stiff leg pad constructions. This indicates that future research should investigate how to improve leg pad fit in addition to studying the knee guard and how it can improve a goaltender's interaction with their equipment.

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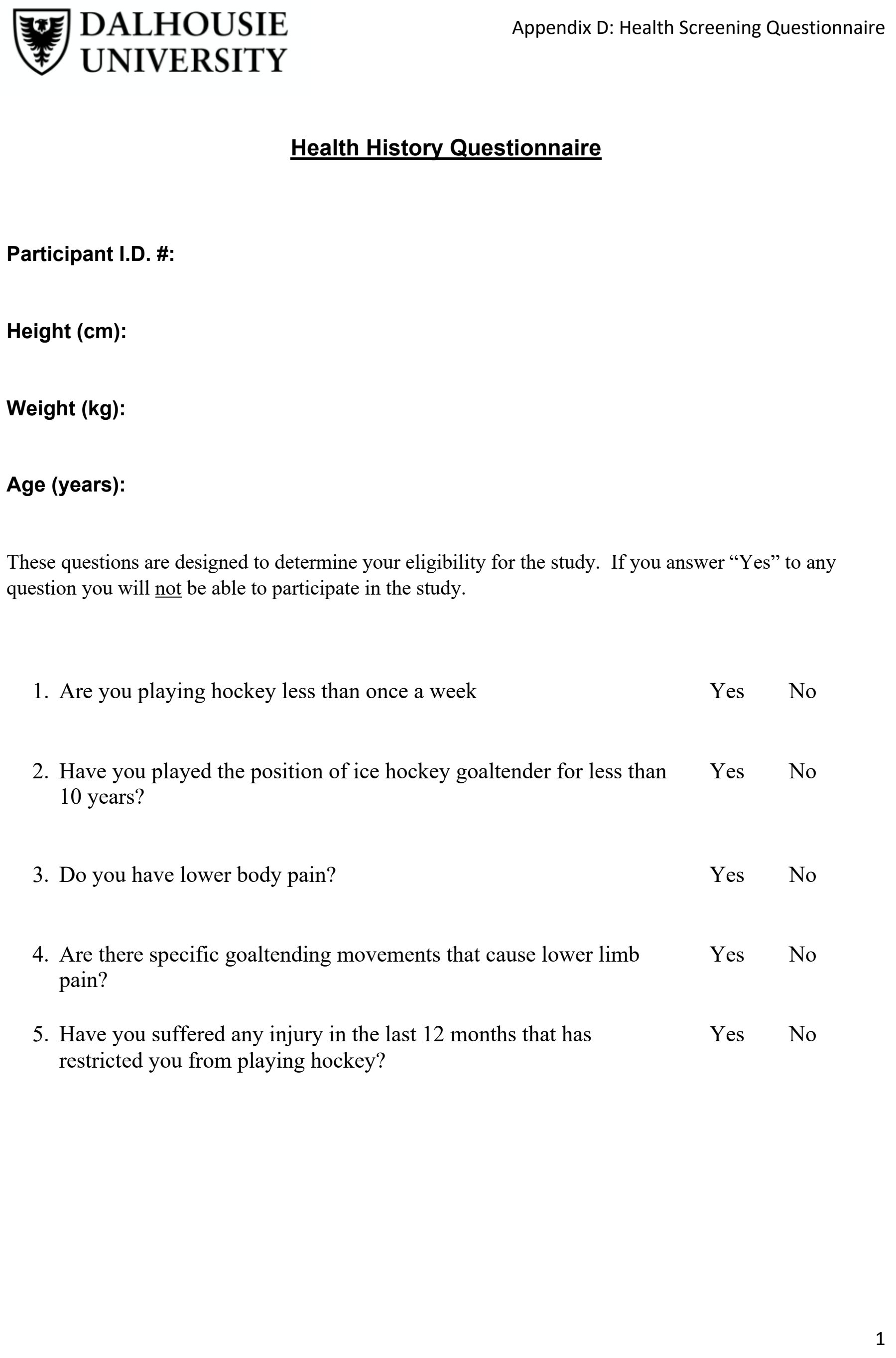
Appendix A: Health History Questionnaire



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Appendix D: Health Screening Questionnaire

Health History Questionnaire

Participant I.D. #:

Height (cm):

Weight (kg):

Age (years):

These questions are designed to determine your eligibility for the study. If you answer "Yes" to any question you will not be able to participate in the study.

1. Are you playing hockey less than once a week Yes No
2. Have you played the position of ice hockey goaltender for less than 10 years? Yes No
3. Do you have lower body pain? Yes No
4. Are there specific goaltending movements that cause lower limb pain? Yes No
5. Have you suffered any injury in the last 12 months that has restricted you from playing hockey? Yes No

Appendix B: Letter of Information & Informed Consent

Letter of Information and Informed Consent Document

Project Title: Goaltender leg pad fit, responsiveness and performance

You are invited to take part in a research study being conducted by Dr. Ryan Frayne, an Instructor of Kinesiology from the School of Health and Human Performance at Dalhousie University. Your participation in this study is voluntary and you may withdraw from the study at any time without any repercussions to your studies or employment. The information below tells you about what you will be asked to do for the study and about any benefit, risk, or discomfort that you might experience.

Who will be conducting the research?

The principal investigator will be Dr. Ryan Frayne from the school of Health and Human Performance at Dalhousie University. Dr. Frayne can be contacted via email (Ryan.Frayne@dal.ca) or telephone at (902) 494-6499 should you have any questions or concerns about the study. The lead graduate researcher, Mr. Alex Peddle, will be assisting and conducting data collection and analysis.

Purpose and Outline of the Research Study:

Modern goaltender leg pads are designed to minimize impact forces to the lower body and have been designed with molded foam cores [2] and large medial leg padding that improves goaltender balance while they are in a kneeling position. However, these equipment developments were intended to improve performance, while complying with league regulations, and may not have considered how the PPE would affect goaltender kinematics and kinetics. Stefanyshyn et al., suggests that sport equipment has evolved, through materials engineering at a faster pace than biomechanical evaluations, creating a gap in the understanding in the effects of PPE on performance [3]. As a result, sport equipment manufacturers, such as CCM Hockey, require biomechanical evaluations of their innovative new products to ensure leg pad fit, responsiveness and performance are all improved simultaneously.

In a recent project quantifying butterfly drop performance, it was identified that a leather lower leg strap located high on the lower leg is strongly correlated to leg pad peak butterfly drop velocity [1]. As a result, CCM Hockey has requested an investigation into the performance effects of their new elastic strap system when placed in two different locations: high lower leg (located just below the knee) and middle lower leg. There is also evidence suggesting that stiff goaltender leg pads have significantly larger transverse plane rotations compared to flexible leg pads during butterfly motions [1], resulting in the leg pads staying externally rotated upon the recovery from the butterfly movement. This extra movement in the stiff leg pads may be related to the decrease in peak butterfly drop velocity performance observed when comparing a stiff leg pad model to a flexible model [4].

Therefore, the purpose of this research is to understand the influence that the new elastic leg pad strapping system has on stiff and flexible leg pad designs, as well as identify the ideal location of an elastic lower leg strap system for improving leg pad fit, responsiveness and performance.

Who can participate in the study?

You may participate in this study if you are between 18 and 40 years of age and are between 165 and 188 cm (5'5" – 6'2") in height.

You may NOT participate in this study if you:

- do not have greater than 10 years of ice hockey goaltender experience
- do not play a minimum of once a week
- have hip or knee pain
- have movement restrictions at either the hip or knee
- have suffered a hip or knee injury in the last 12 months

What you will be asked to do?

We will measure your height, and floor to knee height, to ensure you are eligible to participate in the study. We will also collect your weight and lower leg circumference for participant demographics. We will also further explain the equipment and procedures used for the study to ensure you are fully informed. Please come prepared with appropriate attire that you would normally wear underneath your pads, as well as an athletic top that will not impede movement.

Testing procedure: The study will involve 1 visit lasting approximately 1.5-2 hours. Once the consent form has been signed you will be asked to get your skates on and 1 of the 3 goaltender leg pad conditions will then be assigned to you. Research assistants will assist with the application of the equipment to ensure that the pressure sensors and motion tracking clusters are not damaged during preparation. Once dressed you will be given 5 minutes to become familiar with the ice surface and warm up. Then testing will begin, where you will be asked to perform 4 typical goaltender movements 3 times each in a randomized order. Then your equipment condition will change, and we will repeat the movements within the new condition. Testing will be conducted on synthetic ice with an NHL goal crease in-lay (Figure 1).

Figure 1: Depiction of lab setup with NHL regulation goal crease in-lay on the synthetic ice.

The equipment conditions are:

- Stiff leg pad with high lower leg elastic strap
- Stiff leg pad with middle lower leg elastic strap
- Flexible leg pad with middle lower leg elastic strap

The goaltender movements are (Figure 2):

- Full butterfly with recovery
- Reverse vertical horizontal (RVH: left post) to recovery to top of crease
- Backside edge butterfly push to the left
- T-push to the left

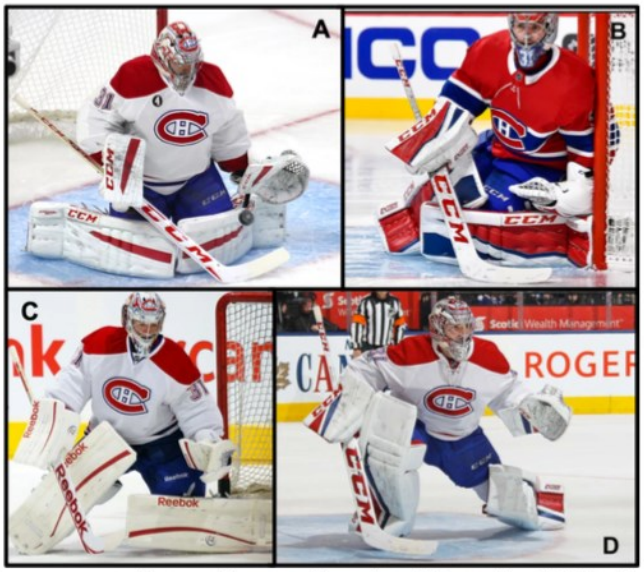


Figure 2: These are the movements that participants will conduct. A) Butterfly, B) RVH with recovery to feet, C) Backside Edge push, D) T-push.

What is the Optitrack 3D Motion capture camera system?

The OptiTrack passive 3D motion capture camera system is a non-invasive method for quantifying participant bodily motion. In this study there will be rigid body clusters located on the front of the goaltender leg pads (boot region, shin, knee and thigh) and 5 markers taped to the outside of your skate. The skate markers will be located near your Achilles, calcaneus, lateral malleolus, 5th metatarsal and over the cuboid bone. You will also have marker clusters attached to your body: Pelvis, thigh and lower leg (Figure 1). All markers are wireless and their positions are collected using infra-red light that reflects from the surface of the markers. The camera system will only identify the location of the leg pads, skate and your leg; Therefore, no identifiable information will be collected when using these cameras. This movement data will be used to measure the location of your leg pad with respect to your lower leg and goaltender performance during movements (eg. butterfly drop velocity). By signing this document, you consent to having your leg pad, skate and leg motion measured using this camera system.

Possible Benefits, Risks and Discomforts?

There is no direct benefit to participating in this study. Your participation will provide integral information for CCM Hockey regarding leg pad fit, responsiveness and performance and how those variables change in different leg pad models (Stiff versus flexible) and when the location of the lower leg elastic strap is in a high or middle leg position. There is little injury risk associated with participating in this study as all of these movements are being completed without pucks and are motions that you would conduct every day in practices or games.

Compensation / Reimbursement:

After testing is completed, participants will be compensated $20.00 for their efforts and given a CCM hockey baseball hat. If you decide to stop participating, once you have begun the study, then you will still be compensated $20.00 and given the CCM hockey baseball cap.

Privacy and Confidentiality:

Information that you provide us will be kept private. Only the research team working on this research project at Dalhousie University will have access to this information. We may describe and share our group findings in oral and/or poster presentations at conferences or seminars. We will also submit our group findings for publication to an academic journal. The group findings may also be presented to CCM hockey (Montreal QC). We will ensure that no subject is identified during any dissemination of this research. This means that ***you will not be identified in any way in our reports and presentations***. The people who work with your information have special training and have an obligation to keep all research information private. Also, we will use a participant number (not your name) in our written and computerized records so that the information we have about you contains no identifiers (ie. Name, age, sex, etc.). All your identifying information will be kept in a separate file, in a locked cabinet, in a locked room in the Dalplex. All electronic records will be kept secure in a password-protected, encrypted file on the researcher's laboratory computer (or on a Dalhousie University secure server).

If You Decide to Stop Participating:

You are free to leave the study at any time. If you decide to stop participating at any point in the study, you can also decide whether or not to have any information/data obtained to that point destroyed. You may decide to have your information and data removed up to 1 month after your day of testing. After that time, it will be incorporated into the group results and analyzed.

How to Obtain Results?

You can obtain either group results or your individual results by including your contact information at the end of the signature page and selecting one of the following result options; Group results, Individual results (ie. Your results), Both, or Neither. Dr. Frayne will send your desired results to you via your preferred method.

Questions:

We are happy to talk with you about any questions or concerns that you may have about your participation in this research study. Please contact Dr. Ryan Frayne at (Ryan.Frayne@dal.ca) or (902) 494-6499, at any time. We will also tell you if any new information comes up that could affect your decision to participate.

If you have any ethical concerns about your participation in this research, you may also contact Catherine Connors, Director, Research Ethics, Dalhousie University at (902) 494-1462, or email: ethics@dal.ca

Consent for participation in the research study

Project Title: Goaltender leg pad fit, responsiveness and performance

I, ______________________________ have read the explanation about this study. I have been given the opportunity to discuss it and my questions have been answered to my satisfaction. I agree to take part in this study. However, I realize that my participation is voluntary and that I am free to withdraw from the study at any time.

[ ] I have selected "No" to each of the questions in the Musculo-Skeletal Health Questions.

____

Participant's Signature

______________________________ ______________________________

Print Name of Participant Date

Do you consent to using de-identified photos of you for publication, presentation or reports? All photos would be of you conducting the research study and your face would be covered to ensure that you were not identifiable. Please sign below if you consent to using your de-identified photo.

____

Participant's Signature

Please send me (please circle):

Group Results	**Individual Results**	**Both**	**Neither**

Please contact me at (please list a phone number, e-mail address, or mailing address):

Phone Number: ______________________________

E-mail Address: ______________________________

Mailing address: ______________________________

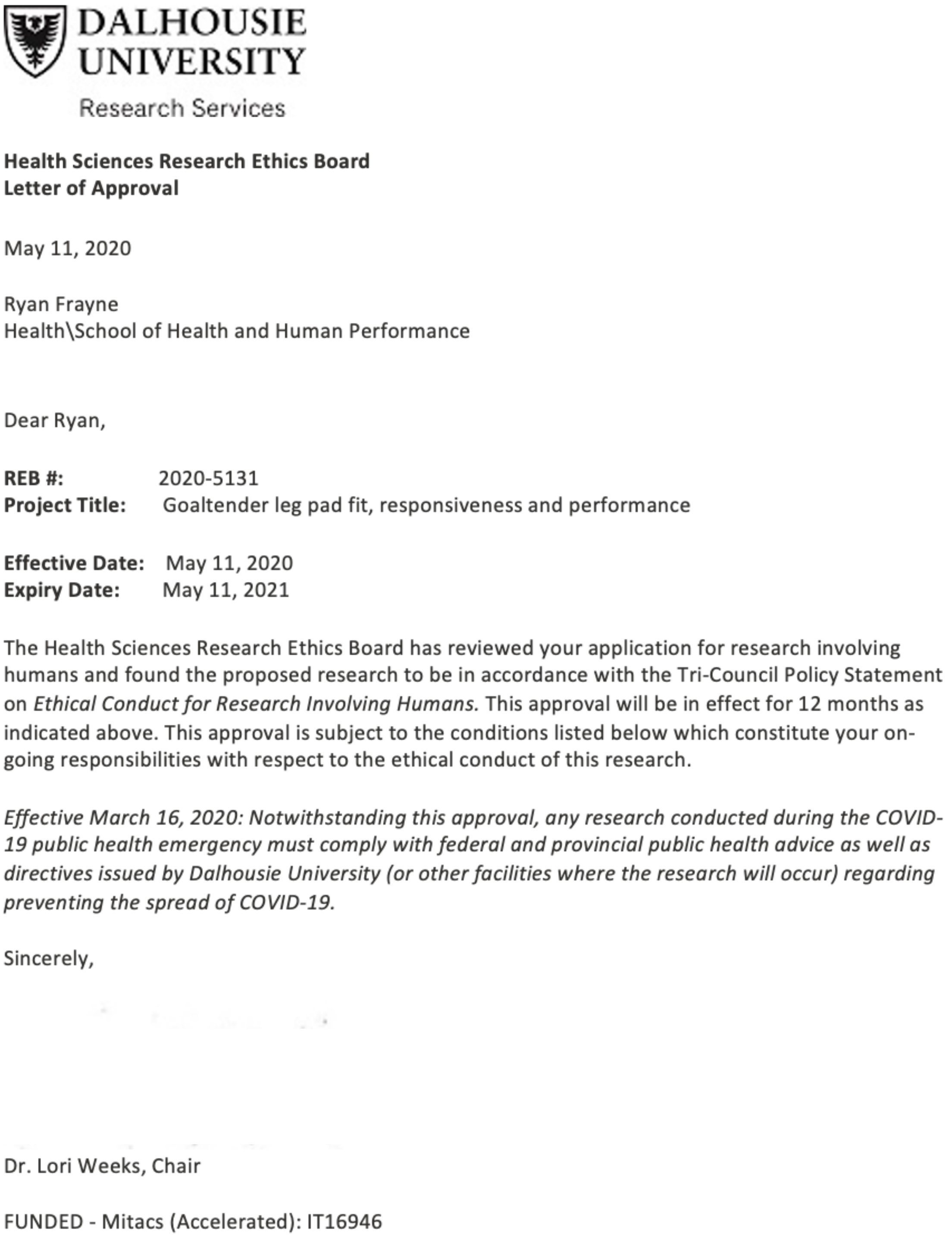
Person obtaining consent (Researcher)

I confirm that I have explained the nature and purpose of the study to the participant named above and have answered all questions. In my judgment the participant is voluntarily and knowingly giving informed consent to participate in this research study.

______________________________ ______________________________

Print Name Signature:

Appendix C: Ethics Approval



DALHOUSIE
UNIVERSITY
Research Services

Health Sciences Research Ethics Board
Letter of Approval

May 11, 2020

Ryan Frayne
Health\School of Health and Human Performance

Dear Ryan,

REB #: 2020-5131
Project Title: Goaltender leg pad fit, responsiveness and performance

Effective Date: May 11, 2020
Expiry Date: May 11, 2021

The Health Sciences Research Ethics Board has reviewed your application for research involving humans and found the proposed research to be in accordance with the Tri-Council Policy Statement on *Ethical Conduct for Research Involving Humans.* This approval will be in effect for 12 months as indicated above. This approval is subject to the conditions listed below which constitute your on-going responsibilities with respect to the ethical conduct of this research.

Effective March 16, 2020: Notwithstanding this approval, any research conducted during the COVID-19 public health emergency must comply with federal and provincial public health advice as well as directives issued by Dalhousie University (or other facilities where the research will occur) regarding preventing the spread of COVID-19.

Sincerely,

Dr. Lori Weeks, Chair

FUNDED - Mitacs (Accelerated): IT16946