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# The Effects of Ice Hockey Goaltender Leg Pads on Safety and Performance

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Graduate Program in Kinesiology  
A thesis submitted in partial fulfillment of the requirements for the degree in Doctor of Philosophy  
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## Abstract

Ice hockey goaltenders have the highest percentage of cam-type femoroacetabular impingement (FAI). The exact cause of these injuries in goaltenders remains unknown; however, it has been suggested that common goaltender movements and a goaltender's underlying hip pathology may be contributing factors. The butterfly save technique, commonly used by goaltenders, has been linked to FAI. Simply stopping these movements would likely be detrimental to goaltender performance. Therefore, changing other aspects of goaltending, such as altering the goaltender equipment, should be considered. The overall objective of this thesis was to understand how ice hockey goaltender leg pads influence both the safety and performance of goaltenders. This was achieved through three projects: quantifying the effect of varying goal pad styles and modifications on goaltender hip kinematics, quantifying goal pad kinematics with respect to the goaltender's body, and quantifying interface forces between the goaltender and their equipment to understand the biomechanical interactions. A new kinematic marker set and a novel interface force research protocol were developed in Chapters 2 and 4, respectively. Chapter 2 identified that, on average, 64% of goaltenders exceeded their active internal rotation range of motion limit during butterfly movements. Butterfly hip kinematics were not altered in four different styles of goal pad (Chapter 2). However, in Chapter 2 and 3 performance differences were observed between the four goal pad conditions, suggesting that a flexible-tight goal pad will produce the fastest butterfly drop velocity and butterfly width without statistically altering hip kinematics. In Chapter 4, there were no interface force differences between a stiff-wide and a flexible-tight goal pad condition; however, peak medial ice contact forces averaged 1073.8 N and 1221.8 N, respectively. These ice contact forces combined with compromising hip kinematics may increase a goaltender's risk of developing FAI. Therefore, understanding the biomechanical interactions between a goaltender's equipment and their body will help manufacturer's develop equipment that minimizes hip kinematics and peak contact forces that can cause intra-articular hip injuries in goaltenders.

## Keywords

Ice hockey, goaltending, goaltender leg pads, kinematics, hip, femoroacetabular impingement, interface forces

## Co-Authorship Statement

This thesis contains material from one published manuscript (Chapter 2), one submitted manuscript (Chapter 3) and a manuscript that is being prepared for submission (Chapter 4). Ryan Frayne was the primary author of all the chapters contained in this thesis. Dr. James P. Dickey (Associate Professor in the School of Kinesiology, Faculty of Health Sciences, Western University) co-authored Chapters 2-4; Dr. Leila Kelleher (Professor, Faculty of Fitness and Health Promotion, Kinesiology, Humber College) and Peter Wegscheider M.Sc. (School of Kinesiology, Faculty of Health Sciences, Western University) co-authored Chapter 2. Alex Harriss (PhD Candidate, School of Kinesiology, Faculty of Health Sciences, Western University) co-authored Chapter 4.

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# Table of Contents

Abstract .....	i
Co-Authorship Statement.....	iii
Acknowledgments.....	iv
List of Figures .....	ix
Chapter 1 .....	1
1 Introduction: Background and Rationale .....	1
1.1 History of ice hockey goaltending .....	1
1.2 Goaltender Injury .....	3
1.2.1 Goaltender Hip Injury .....	4
1.3 Goalie Equipment .....	7
1.4 Purpose.....	12
1.4.1 Chapter 2 Purpose .....	12
1.4.2 Chapter 3 Purpose .....	12
1.4.3 Chapter 4 Purpose .....	13
1.5 References.....	14
Chapter 2.....	18
2 Development and verification of a kinematic protocol to quantify hip joint kinematics: an evaluation of ice hockey goaltender leg pads on hip motion .....	18
2.1 Summary .....	18
2.2 Introduction.....	19
2.2.1 Purpose.....	20
2.3 Methods.....	21
2.3.1 Subjects .....	21
2.3.2 Hardware.....	22
2.3.3 Marker Sets .....	22
2.3.4 Testing Protocol .....	23
2.4 Results.....	25
2.5 Discussion .....	29
2.6 Conclusion .....	32
2.7 References.....	34
Chapter 3.....	36
3 Quantifying ice hockey goaltender leg pad kinematics and the effect that different leg pad styles have on performance .....	36
3.1 Summary .....	36

3.2	Introduction.....	37
3.2.1	Purpose.....	38
3.3	Methods.....	38
3.3.1	Participants.....	38
3.3.2	Hardware.....	38
3.3.3	Marker Sets .....	39
3.3.4	Testing Protocol .....	40
3.4	Results.....	43
3.5	Discussion .....	45
3.6	Conclusion .....	49
3.7	References.....	50
Chapter 4.....		52
4	Quantifying interface forces between goaltenders’ legs and leg pads in ice hockey...	52
4.1	Summary.....	52
4.2	Introduction.....	53
4.2.1	Purpose.....	55
4.3	Verification Methods .....	53
4.3.1	Verification Apparatus.....	55
4.3.2	Location of Sensels with respect to the pads .....	58
4.3.3	Verification Protocol.....	58
4.4	In vivo equipment-goaltender interface experiment.....	55
4.4.1	Hardware.....	59
4.4.2	Testing Protocol .....	61
4.5	Results.....	62
4.6	Discussion.....	66
4.6.1	Goaltender leg pad-Goaltender Interaction.....	68
4.6.2	Limitations/Future Directions.....	66
4.7	Conclusion .....	70
4.8	References.....	73
Chapter 5.....		76
5	Discussion .....	76
5.1	Summary of Results/Implications.....	76
5.2	Future Directions .....	81
5.3	Conclusion .....	82
5.4	References.....	84
6	Appendices.....	86
6.1	Appendix A (Chapter 2 and 3 Ethics approval).....	86
6.2	Appendix B (Chapter 2 and 3 Ethics Revision).....	87



6.3 Appendix C (Chapter 4 Ethics Approval).....	88
6.4 Appendix D (Chapter 2 Figure Permissions).....	89
Curriculum Vitae .....	90

## List of Tables

Table 2.1: Participant demographics with the average weekly hours of ice time and age of control leg pad condition .....	21
Table 4.1: Demographics table with weekly hours of ice time.....	59

## List of Figures

Figure 1.1: Carey Price performing the butterfly save technique. This image was modified from <http://ingoalmag.com/gear/close-carey-prices-new-ccm-extreme-flex-2/> ..... 1

Figure 1.2: (left) A goaltender adopting the reverse VH Position where the goaltender's leg closest to the post is horizontal while the back leg is vertical. (Right) A goaltender adopting the VH position where the goaltender's leg closest to the post is vertical while the back leg is horizontal. .... 2

Figure 1.3: Image of a normal healthy hip joint (A) and of a hip joint with Cam-typed deformity FAI (B). This figure was modified from <http://orthoinfo.aaos.org/topic.cfm?topic=a00571>. .... 6

Figure 1.4: (Left) Medial and anterior view of a 1960's era ice hockey goaltender leg pad. (Right) Patrick Roy performing a butterfly in a traditional pair of goalie pads built similar to the 1960's goalie pads. Note the left goal pad is face down on the ice leaving the leg exposed to shots. .... 8

Figure 1.5: (Left) Medial and anterior view of modern goaltender leg pads. The medial view (far left) shows the knee riser (circle) and the built up medial calf support (rectangle) that goaltenders use to balance upon during butterfly movements. (Right) Carey Price performing a butterfly in a modern goaltender leg pad. This figure was modified from Julie Gauthier CCM goalie summit. Note the medial portion of the goaltender leg pad that the goaltender lands on when in the butterfly..... 9

Figure 1.6: Lateral view of two different styles of goalie pad from Reebok-CCM hockey. The left goalie pad is a CCM E-Flex II and the right goalie pad is a CCM Premier. .... 9

Figure 1.7: A tight leg channel setup (left) and a wide leg channel set up (right). Note that the width of the orange depicts leg channel width..... 10

Figure 2.1: The thigh rigid body was designed to strap and Velcro to the antero-lateral thigh with a Velcro patch beneath the rigid body and a strap that wrapped the thigh. Figure 2.1B: The leg rigid body was designed to sit off the posterior mid-calf and did not interfere with the goalie pads or straps. Figure 2.1C: Shows the location of the equipment marker set including markers on the thigh, leg, leg pads, skate, blocker and glove..... 23

Figure 2.2: (Left; a-d) A representative goaltender's hip kinematic curves when performing a full butterfly with a single leg recovery (subject 5). (Right; e-h) A representative goaltender's hip kinematic curves when performing a full butterfly and a double leg recovery (subject 3). The solid curve is the mean, the dashed line is  $\pm 1$  standard deviation and the vertical solid line depicts the moment the goaltender's knee hit the ice. .... 26

Figure 2.3: Each subject's average peak internal rotation in the four goalie pad conditions, with their active and passive ROM limits. Subjects are ordered from least to greatest internal rotation with respect to active ROM in the control goalie pad condition. .... 27

Figure 2.4: Each subject`s butterfly width in the four goalie pad conditions. Subjects are ordered from least to greatest internal rotation with respect to active ROM in the control goalie pad condition. .... 28

Figure 2.5: Scatter plot of normalized hip internal rotation and butterfly width in the four goalie pad conditions. These variables are strongly correlated ( $r= 0.95$ ). Increasingly negative ..... 28

Figure 3.1: Markers located on the left pad, gloves, pelvis, thigh and leg. The leg rigid body was elevated 5 cm off the back of the shank so that it did not interfere with the goal pad straps. .... 39

Figure 3.2: The scheme depicting the kinematic motions of the pad with respect to the goaltenders leg in each of the three planes of motion. .... 42

Figure 3.3: Goal pad with respect to the goaltenders' leg in the four goal pad conditions during the butterfly drop (A-C) and butterfly recovery (D-F). Note that the graph panels have different scales between planes. .... 44

Figure 3.4: Each participant's average butterfly drop velocity in the four goal pad conditions. The horizontal lines indicate the group means for each of the goal pad conditions. .... 45

Figure 4.1: A posterior view of a stiff-wide goal pad. The knee cradle is the combination of the medial knee riser (blue), anterior foams and a lateral flap (not seen in this image but is a fixture on the Flex-Tight pads). The medial knee riser is constructed of a 1.27 cm thick layer of soft foam on the inside and approximately 3.81 cm thick dense foam on the outside. The calf wrap (orange) has medial and lateral foam flaps that wrap around the leg of the goaltender. There is also a built up medial region on the calf wrap that provides stability when the goaltender is in the butterfly position. .... 54

Figure 4.2: Setup for pressure sensor verification. The testing mechanism with load cell and effective mass were placed within the leg channel of the goal pad and fastened using the goal pad leg straps. .... 56

Figure 4.3: Left, view of a goal pad leg channel. Middle, the orange highlights depict the locations where loop Velcro was sewn into the leg channel to provide sensor attachment. Right, the custom sensor sleeve is attached to the loop velcro to minimize sensor shifting during goaltender movement. Note: the 3200E sensor is not visible in the right image because it is located below the top right region of the CONFORMat sensor (ie. the medial knee riser location). .... 57

Figure 4.4: Kinematic marker setup on the goal pad (Thigh, knee, shin and boot with 3 individual markers located on the distal lateral aspect of each the left and right leg pad. Passive motion capture cameras are visible at the top of the figure and the synthetic ice with the goal crease inlay, used to replicate on-ice conditions, is visible at the bottom of the figure. The kinematic markers located on the gloves were visual and only used for tracking orientation. .... 60

Figure 4.5A: Relationship between the load cell and the interface forces during verification testing ( $r = 0.95$  and a linear relationship of  $y = 0.998x$ ). ..... 63

Figure 4.6: A forest plot of the mean differences, with adjusted confidence intervals (CI = whiskers), between the Flex-Tight and Stiff-Wide goal pad peak forces during the 3 phases of butterfly and on each of the 3 areas of the goal pad. Paired comparison P-values and the adjusted percent CI (adjusted based on modified Bonferroni) are also displayed. Note: a positive difference indicates that the Flex-Tight condition had a larger peak force compared to the Stiff-Wide goal pad condition. .... 64

Figure 4.7: A) Force-time ensemble average graph of the five butterfly movements performed by an exemplary subject wearing the Stiff-Wide condition. The average forces of each goal pad area (medial, anterior and lateral) over the entire butterfly movement, with vertical areas representing the three phases of the butterfly. The black line depicts the displacement of the top of the left goal pad. The nine intensity charts beneath the graph depict the dispersion of forces at the approximate moment of peak force during each phase of the butterfly (initiation B-D, ice contact E-G, and butterfly recovery H-J). The black area reflects void data as there was no sensel in that region, and the shade of blue qualitatively reflects the force magnitude. Dark blue = zero force, and gradients between light blue and white reflect increased force magnitude. Note: the three medial, anterior and lateral intensity charts correspond to the orange regions on the goal pad image (panel K). .. 66

Figure 4.8: Traditional boot strap setup (left) and the recent no boot strap setup (right pad) being adopted by the ice hockey goaltending community. Notice the position of the pads with respect to the skates between the strap setups. The pad in the no strap condition is sitting higher on the goaltender`s leg. Figure was modified from <http://ingoalmag.com/news/power-to-push-new-ccm-extreme-flex-ii-boot-break/>. .... 68

## Chapter 1

### 1 Introduction: Background and Rationale

#### 1.1 History of ice hockey goaltending

The “stand up” style of goaltending was commonly used until the 1980’s and was partially dictated by the goalie equipment that was available at the time. The implementation of goalie masks in 1959 allowed goaltenders to drop to their knees without the fear of facial injuries. Goalie equipment technology slowly advanced through the 60’s and 70’s, and the stand-up style remained the primary form of goaltending used in the National Hockey League (NHL). In 1985 Patrick Roy came into the NHL and, along with his goalie coach Francois Allaire, introduced a new goaltender save technique called the “butterfly”. This save technique is characterized by a goaltender dropping to their knees and flaring their ankles laterally to block the lower half of the net with their leg pads (Figure 1.1).



**Figure 1.1:** Carey Price performing the butterfly save technique. This image was modified from <http://ingomag.com/gear/close-carey-prices-new-ccm-extreme-flex-2/>

It has been estimated that NHL goaltenders, regardless of style, drop into the full butterfly 34 times ( $\pm 6$  butterflies) in a single game<sup>4</sup> and upwards of 300 times in a

practice<sup>7</sup>. These values may be an underestimation because, for the last 5 years, NHL goaltenders are also using modified butterfly save techniques for post play known as the vertical horizontal (VH) and the reverse vertical horizontal (RVH). During these movements goaltenders adopt a half butterfly position to seal against the post and ice (Figure 1.2). This position blocks both the vertical and the horizontal shooting angles on plays close or below the goal line and can place the hips in a flexed and internally rotated state. This is particularly prominent in the RVH save position. The large number of butterfly movements, and adapted butterfly movements like the VH/RVH, that professional goaltenders perform has been identified as a possible reason for the high prevalence of hip related injuries in goaltenders<sup>25, 34</sup>.



**Figure 1.2:** (left) A goaltender adopting the reverse VH Position where the goaltender's leg closest to the post is horizontal while the back leg is vertical. (Right) A goaltender adopting the VH position where the goaltender's leg closest to the post is vertical while the back leg is horizontal.

## 1.2 Goaltender Injury

Research on ice hockey injuries has suggested that forwards and defensemen make up the bulk of injuries on a hockey team<sup>19, 21</sup>. In 1988, Lorentzon et al. followed an elite Swedish hockey team for 3 seasons and concluded that goaltenders, defensemen and forwards had an injury rate of 39.2, 107.8 and 71.8 per 1000 hours of game play, respectively<sup>19</sup>. Similarly, 7 NCAA hockey teams from 1987-1990 observed that goaltenders, defensemen and forwards had an injury rate of 6.84, 9.9 and 11.4 per 1000 hockey exposures (practice and game), respectively<sup>21</sup>. More recent research from the NCAA (2001-2002 hockey season) observed a similar distribution of injuries, with goaltenders having the lowest injury rate at 2.7 per 1000 hockey exposures compared to 5.0 and 5.1 for defensemen and forwards, respectively<sup>11</sup>. However, simple interpretation of this ice hockey injury data is complicated because of changes to ice hockey equipment during this time, rule changes and in particular, the number of players used at each position.

Differences in injury rates observed between the elite Swedish hockey league and the NCAA may be due to improvements in equipment. For example, modern equipment has a hard outer cap that is used to disperse impact forces across the entire equipment-body interface. Alternatively, differences in rules (ie. optional face protection in the Swedish elite league versus mandatory face protection in the NCAA) and game style (ie. men playing on a larger ice surface in the Swedish elite league may facilitate greater peak player velocities versus young adults playing on a smaller ice surface in the NCAA<sup>11</sup>) may be contributing. One of the most important differences is the inclusion of both game and practice injury data in the NCAA studies, which would have decreased the injury rates, since injury rates in practices are drastically lower (2.2 - 2.9 per 1000 practice exposures compared to 12.1 – 18.69 for games<sup>21, 11, 1</sup>). Another reason that injury rates in hockey are difficult to interpret are the number of players quantified at each position. A typical game has 2 goalies, 8 defensemen and 12 forwards participating. The differences in sampling may be misrepresenting goaltender injury rates. For example, a Finnish study observing 7 hockey teams for a single season observed 5 goaltender concussions<sup>22</sup>, while Flik et al.'s study observed 0 goaltender concussions<sup>11</sup>. Discrepancies like this identify



that studies focused on goaltender injuries are necessary to better understand the incidence rate and types of injuries that goaltenders are sustaining.

LaPrade et al. conducted a comprehensive goaltender injury study analysing injuries in the NCAA from 2000 -2007. They reported low injury rates for goaltenders at 0.5 (men) and 0.72 (women) per 1000 game exposures <sup>16</sup>. These values give the appearance that goaltenders are seldom injured, but other studies have reported goaltender injury rates as high as 6.84 per 1000 hockey exposures <sup>21</sup>. Taken together, these findings seem to indicate that goaltenders are more commonly injured during practices than in games. According to Flik et al. 37.6% of hockey player injuries, during practice, are goaltender related. The high number of practice exposures, 77% of yearly hockey exposure <sup>11</sup>, combined with the estimate that goaltenders perform upwards of 300 butterfly movements in a practice <sup>7</sup>, may explain why goaltenders are the most frequently injured player in a practice <sup>11</sup>. Therefore, injuries in goaltenders should be considered separately than those in forwards and defensemen, as aggregation masks the type and incidence rates of goaltender injuries. Forwards and defensemen suffer a large number of game injuries that are the result of impacts with the boards or players <sup>11</sup>, while goaltenders are more commonly injured during practices and suffer injuries that affect the hip <sup>16</sup> and are thought to be related to overuse <sup>21</sup>.

### 1.2.1 Goaltender Hip Injury

Goaltenders commonly experience hip injuries <sup>25</sup>. As mentioned earlier, goaltenders frequently adopt the butterfly position <sup>4,7</sup>, or variants like it such as the VH or the RVH. It is thought that the repeated combination of compromising hip positions and transient forces during the butterfly/modified butterfly movements are environmental factors that may contribute to the high incidence rate of hip injuries in goaltenders <sup>25,3</sup>.

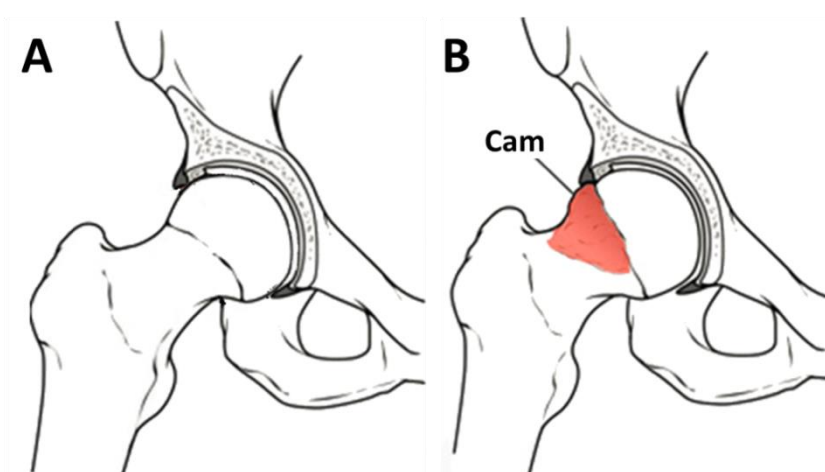
As mentioned earlier, the butterfly save technique is characterized by goaltender's dropping to their knees and flaring their ankles laterally to block the lower portion of the net with their leg pads. The first study to investigate the butterfly save technique's effect on goaltender hip kinematics identified that this position places the hip in a flexed and internally rotated state when the goaltender's knees impact the ice. The flexion and

abduction motions during the butterfly were within a goaltender's range of motion; however, hip internal rotation commonly reached the goaltender's passive range of motion limit<sup>34</sup>.

An on ice examination of 3 common goaltender movements (skating, butterfly drop and recovery) identified that hip internal rotation was the most extreme planar motion that goaltenders performed. The amount of hip internal rotation during the butterfly save technique was only exceeded by that during deceleration while skating<sup>33</sup>. It is important to note that the skating task required the goaltender to push from their left post to the top of the crease; therefore, the reduction of the forward momentum was accompanied by a large amount of hip internal rotation. Regardless of the movement, large internal rotations appear to distinguish goaltenders from other athletic populations. The repetitive hip internal rotation motions to the full end-range may be the primary precursor to femoroacetabular impingement (FAI) in hockey goaltenders<sup>33</sup>.

It has been reported that there are multiple etiological factors responsible for the development of FAI<sup>29,28</sup>. For example, unrecognized abnormal bony morphology of the acetabulum and/or of the femur<sup>29</sup> that occurs before full skeletal maturity may cause individuals to develop disorders like osteoarthritis<sup>25</sup>. These types of acetabular and femoral deformities may compromise the clearance of the hip during specific hip motions<sup>13</sup> resulting in abutment between the acetabular rim and the femoral neck. However, individuals with normal hip morphology that undergo supraphysiologic movement, such as goaltenders when they perform the butterfly<sup>12,38</sup> and other goaltender movements (ie. skating<sup>37</sup>), may also achieve similar acetabular and femoral neck abutments<sup>13</sup>. Wyss et al. determined that the degree of hip internal rotation with a flexed hip posture, like that of the butterfly movement, is limited by bony structures<sup>39</sup>. This suggests that movements, like the butterfly and specific skating positions, may place the hip in compromised positions that can result in an abutment of the femoral head-neck against the acetabular rim<sup>14,29,3</sup> and potentially lead to the development of hip osteoarthritis<sup>30,13</sup>.

Kubiak-Langer et al. observed that with increasing hip flexion, less hip internal rotation was required to cause an abutment between the femoral neck and acetabular rim in both healthy and positively diagnosed FAI hips<sup>15</sup>. Concurrent hip flexion and internal rotation are common positions that goaltenders are adopting and explain why goaltenders, radiographically, show the highest percentage of cam-type FAI deformity (approximately 7.6% versus 67.5% for forwards and defensemen<sup>18,26</sup>). Cam-type FAI occurs when an enlarged/aspherical junction between the head and neck of the femur<sup>2</sup> is driven into the acetabulum producing damage to the cartilage in the area of the anterosuperior rim of the acetabulum<sup>14</sup> (Figure 1.3). Cam deformities can lead to other intra-articular hip injuries such as labral tears.



**Figure 1.3:** Image of a normal healthy hip joint (A) and of a hip joint with Cam-typed deformity FAI (B). This figure was modified from <http://orthoinfo.aaos.org/topic.cfm?topic=a00571>.

A surveillance study of hip injuries in the NHL revealed that 15% of goaltenders that played a minimum of 1 game in the NHL between the seasons of 2006-2010 suffered an intra-articular hip injury<sup>8</sup>. This is substantially greater than defensemen (6.8%) and forwards (5.0%). Labral tears were the most commonly diagnosed intra-articular hip injury in these elite hockey players<sup>27,8</sup>. The acetabular labrum is a ring of cartilage that surrounds the outer edge of the acetabulum<sup>32</sup>. The labrum deepens the acetabulum and enhances joint stability<sup>10</sup>. Damage to the labrum can occur because of repetitive microtrauma, traumatic events, and capsular laxity (dysplasia)<sup>20</sup>. As mention above, goaltenders are repeatedly performing movements that can cause femoral acetabular

abutment <sup>26</sup> and subsequent labral tears <sup>2</sup>. A study investigating FAI as a cause of early osteoarthritis (OA) observed that all patients with a cam deformity, similar to that of goaltenders <sup>26</sup>, also presented with a separation between the acetabular cartilage and the labrum <sup>2</sup>. Another study investigating goaltenders with hip pain, revealed that 29% also have acetabular dysplasia <sup>26</sup>. Goaltenders are a very unique athletic population and it appears that they are frequently placing themselves in positions that may be damaging their hip joints.

The long term effects of being a goaltender should be considered. 73% of patients with labral damage also have chondral changes that may be contributing to the progression of hip osteoarthritis <sup>20</sup>. With these alarmingly high proportions of hip damage in goaltenders, considerations must be given to methods designed to minimize a goaltender's risk of injury. However, simply telling a goaltender to stop performing damaging movements, such as the butterfly, would likely be detrimental to a goaltender's primary purpose of stopping hockey pucks <sup>33</sup>. Therefore, changing other aspects of goaltending, such as altering the goaltender equipment, should be considered.

### 1.3 Goalie Equipment

As mentioned in section 1.1, the goaltender face mask was the first major development in goalie equipment. It changed the way that goaltenders played the game of hockey by allowing them to drop to the ice to make saves without concern of being hit in the face with a puck. Other pieces of goalie equipment, such as the chest and arm and goalie pads, did not change much throughout the 60-80's. This is evident when observing goalie pads from this era. The primary purpose of goalie equipment was to protect goaltenders from blunt hockey puck trauma. Therefore, padding was primarily located on the anterior surface of the body (Figure 1.4). At the time this worked well because goaltenders were still primary using the "stand-up" style of goaltending. With the introduction of the butterfly save technique, a protection problem arose when goaltenders were in the butterfly save position. The face of the goalie pad would commonly be driven into the ice, leaving the top of the knee and medial/lateral sides of the leg exposed (Figure 1.4).



**Figure 1.4:** (Left) Medial and anterior view of a 1960's era ice hockey goaltender leg pad. (Right) Patrick Roy performing a butterfly in a traditional pair of goalie pads built similar to the 1960's goalie pads. Note the left goal pad is face down on the ice leaving the leg exposed to shots.

Around 2005 goalie equipment developers began to make goaltender leg pads that better suited the butterfly save technique. The introduction of injection moulded foams in goalie pads<sup>17</sup> provided manufactures with a more consistent product that could better maintain shape and withstand the rigors of ice hockey. Shortly after the introduction of moulded foams, goalie equipment manufacturers began to build-up the medial portion of the goalie pad to provide a more stable surface for goaltenders when they adopted the butterfly position (Figure 1.5). For example, the medial knee riser is a prominent fixture on the modern goalie pad. NHL rules and regulations state that it cannot be larger than 7" in length, 5 ½" in width and 2 ½" thick<sup>31</sup>.



**Figure 1.5:** (Left) Medial and anterior view of modern goaltender leg pads. The medial view (far left) shows the knee riser (circle) and the built up medial calf support (rectangle) that goaltenders use to balance upon during butterfly movements. (Right) Carey Price performing a butterfly in a modern goaltender leg pad. This figure was modified from Julie Gauthier CCM goalie summit. Note the medial portion of the goaltender leg pad that the goaltender lands on when in the butterfly.

The NHL's regulations standardize the sizing of goaltender leg pads; however, there remain a number of different styles of goal pads available to consumers. For example, Reebok-CCM hockey has two distinct lines of goalie equipment, the CCM E-flex and the CCM Premier (Figure 1.6). The E-Flex line of goal equipment is built with a bendable foam core at the boot region making this Reebok-CCM's flexible series of equipment, while the Premier line is constructed with a firm foam core in the boot region making it Reebok-CCM's stiff series of goaltender leg pads. Goal pad flexibility is



**Figure 1.6:** Lateral view of two different styles of goalie pad from Reebok-CCM hockey. The left goalie pad is a CCM E-Flex II and the right goalie pad is a CCM Premier.

often judged by the pad's ability to flex and twist at the boot region and flex above and below the knee. Goaltender leg pads also vary in leg channel widths and strap selections. Leg channels can be designed to fit tight to the goaltender's calf or loose to provide more movement between the goaltender's leg and the pad (Figure 1.7).



**Figure 1.7:** A tight leg channel setup (left) and a wide leg channel set up (right). Note that the width of the orange depicts leg channel width.

The different goal pad styles are intended to provide goaltenders with options to improve their performance. However, most goal pad innovations, to date, have been the result of professional player feedback and companies complying with league regulations. These innovations are rarely tested to understand how the various styles and modifications affect a goaltender's safety and performance. Manufacturers have primarily focused on testing goaltender PPE using restitution and material tests, creating a disconnect between traditional PPE performance testing and understanding the effects that equipment has on the human body<sup>5, 30</sup>.

Equipment that surrounds the limbs, like that of ice hockey goaltender equipment, reduces heat dissipation and significantly increases cardiovascular/metabolic costs during incremental exercise<sup>28</sup>. For example, elite goaltenders lose  $\sim 2.9 \text{ L} \pm 0.2 \text{ L/h}$  of sweat in a practice<sup>23</sup>, which equates to  $\sim 3.6\%$  of body mass to an 80 kg goaltender. This may be

harmful for goaltenders because a 2% body mass loss in sweat has been shown to impair power production<sup>6</sup>, endurance<sup>9</sup> and cognitive ability<sup>13</sup>. The biomechanical effects of PPE on the human musculoskeletal system have rarely been studied because it creates a research obstacle, where the equipment obscures the line of sight required by most standard 3D motion capture systems. Therefore, biomechanical PPE testing is often limited to timing tasks, balance assessments and mobility evaluations<sup>5,29,24</sup>. In order for equipment companies to fully understand how their equipment influences the musculoskeletal system, these research obstacles must be overcome.

Wijdicks et al. was the first to attempt kinematic measures with ice hockey goaltender equipment by analyzing hip kinematics when goaltenders performed butterfly movements in 30.5 cm wide goal pads (pre-2005/06 season) and 27.9 cm wide goal pads (current regulation)<sup>34</sup>. They observed that goaltender hip internal rotation was not significantly different between the 27.9 cm and the 30.5 cm wide goalie pads. However, they did observe that goaltenders achieved significantly greater hip internal rotation range of motion when in a pair of new 27.9 cm wide goal pads compared to the participant's own 27.9 cm wide pads ( $20.1^\circ \pm 4.8^\circ$  and  $17.5^\circ \pm 4.8^\circ$ , respectively). This finding led them to suggest that new goaltender leg pads should be broken-in slowly to minimize the amount of hip internal rotation when goaltenders adopt the butterfly position. Unfortunately, they did not quantify performance variables during the butterfly movements, which make it difficult to discern if the goaltenders were performing the butterfly movements in a consistent manner. Therefore, there remains a number of unknowns regarding the effects of PPE on goaltenders, in particular goaltender leg pads.

In order to properly develop athletic PPE, athlete safety (impact reduction and how the equipment changes a goaltender's kinematics and kinetics) and sport performance must be considered during the research and design process because PPE can alter both sport injury and performance variables<sup>30</sup>. Stefanyshyn et al. stated that a perfectly engineered piece of sport equipment may fail if the athlete-equipment interaction is not properly addressed<sup>30</sup>. In order to ensure that this does not occur with ice hockey goal pads, we must first obtain a baseline understanding of the effects that current goaltender leg pad styles have on ice hockey goaltender kinematics and



performance variables during the butterfly movement. This will permit proper scientific comparisons between the current goaltender equipment and any new prototype equipment.

## 1.4 Purpose

The overall objective of this thesis was to understand how ice hockey goaltender leg pads influence both the safety and performance of goaltenders. This was achieved through three projects: quantifying the effect of varying goal pad styles and modifications on goaltender hip kinematics, quantifying goal pad kinematics with respect to the goaltender's body, and quantifying interface forces between the goaltender and their equipment to understand the biomechanical interactions. The development of a research protocol that analyzes the effect of PPE on the human body will not only advance ice hockey goalie equipment, it will also advance the field of personal protective equipment testing by including biomechanical analysis.

### 1.4.1 Chapter 2 Purpose

There were 3 objectives in this research project. The first was to develop and verify a kinematic marker set that quantifies hip kinematics of goaltenders when they are wearing goalie equipment. Second, we used the newly developed marker set to describe goaltender hip kinematics during butterfly movements. In particular, we quantified how closely goaltenders approached their end ranges of motion for active and passive hip internal rotation in 4 goal pad conditions (2 leg channel widths and 2 pad stiffness conditions). Finally, we evaluated the relationship between hip internal rotation and butterfly width (performance).

### 1.4.2 Chapter 3 Purpose

There were two main objectives of this research. The first objective was to quantify and describe the ranges of motion (ROM) between varying leg pad styles (ie. stiffness and leg channel width) with respect to the goaltenders' legs in the sagittal,

frontal and transverse planes. The second was to analyze differences in peak vertical butterfly drop velocity in the varying pad conditions.

### 1.4.3 Chapter 4 Purpose

There were 3 objectives for this research. The first was to develop and verify a system that quantifies the interface forces between ice hockey goaltender leg pads and goaltenders' legs. The second objective was to apply the newly developed equipment-goaltender interface force protocol to quantify the medial, anterior and lateral peak forces during butterfly drop initiation, ice contact and recovery. Two leg pad conditions were studied: a stiff pad with a wide leg channel condition (Stiff-Wide) and a flexible pad with a tight leg channel condition (Flex-Tight). The third objective was to describe goal pad kinetics and the ways in which they apply force to goaltenders' legs during butterfly movements.

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## Chapter 2

# 2 Development and verification of a kinematic protocol to quantify hip joint kinematics: an evaluation of ice hockey goaltender leg pads on hip motion

## 2.1 Summary

The butterfly save technique is commonly used by ice hockey goaltenders and has recently been identified as a potential mechanism for hip joint injuries due to its extreme body positions. Therefore, the purpose of this research project was to create a new kinematic protocol that could be used to quantify hip kinematics and butterfly performances while wearing four different goalie pads. The new marker set used marker clusters attached to the lateral thigh and posterior leg. This marker set was verified by comparing it to a calibration anatomical system technique (CAST) marker set during passive range of motion tests. 12 goaltenders performed 5 butterfly movements in 4 different styles of goalie pad (Control, Flexible-Wide leg channel, Flexible-Tight leg channel and Stiff-Wide leg channel). The grouped RMS differences and standard deviations calculated during verification were  $1.43^{\circ}$  ( $\pm 0.41^{\circ}$ ),  $1.0^{\circ}$  ( $\pm 0.39^{\circ}$ ) and  $3.32^{\circ}$  ( $\pm 1.32^{\circ}$ ), for hip flexion/extension, ab/adduction and internal/external rotation, respectively. There was no significant main effect of goal pad condition on the peak amount of hip internal rotation; however, there was a significant main effect of goal pad condition on the butterfly width ( $P=0.022$ ). Post hoc comparisons revealed that the butterfly width was significantly smaller in the control pad condition compared to the Flex-Tight pads ( $P=0.03$ ). The new marker set enabled measurements of hip joint kinematics while wearing protective equipment that are not possible with other marker sets. Inter-individual variations in performance of the butterfly technique influenced the amount of hip internal rotation achieved; however, on average, goaltenders exceeded their active internal rotation range of motion during butterfly movements. These large hip internal rotations may increase the chances that goaltenders sustain a hip injury like femoroacetabular impingement.

## 2.2 Introduction

Ice hockey goalies are susceptible to injury risks including blunt trauma and overuse injuries. Past ice hockey injury research has suggested that goaltenders are less likely to be injured compared to forwards or defensemen, which may be a result of the larger number of forwards/defensemen and the types of injuries that are reported (ie. acute).<sup>11, 12, 8, 18</sup> Variances in data inclusion (eg. missing data from practices) and normalization techniques (eg. hours of exposure versus number of games) have confounded simple interpretation of the ice hockey goaltender injury literature.<sup>12, 11, 10</sup> Recently, a review on hip injuries in the NHL revealed that 15% of goalies that played a minimum of one game in the NHL between the seasons of 2006-2010 suffered an intra-articular hip injury.<sup>6</sup> Although this injury occurs relatively frequently, the direct cause remains unknown.

The butterfly save technique is commonly used by goaltenders<sup>6</sup> and it has been suggested that the combination of the butterfly technique and underlying hip pathologies may expose goaltenders to a higher risk of intra-articular hip joint injuries.<sup>13</sup> The butterfly is characterized by a goaltender dropping to both knees, with their hip flexed and internally rotated in an attempt to block the lower half of the goal net. Bell et al.<sup>1</sup> has estimated that NHL goaltenders drop into the butterfly an average of 34 ( $\pm 6$ ) times a game and upwards of 300 times in a practice.<sup>5</sup> Wyss et al. determined that the amount of hip internal rotation that can occur when the hip is flexed, like that of the butterfly movement, is limited by the bony anatomy.<sup>21</sup> This suggests that the butterfly movement may cause abutment of the femoral head-neck junction against the acetabular rim,<sup>9, 13</sup> placing the labrum in a potentially compromising position.<sup>13, 2</sup> Research has reported that 64% of asymptomatic elite hockey players show evidence of pathologic hip abnormalities.<sup>16</sup> These alarming values, in combination with the butterfly save technique, may be influential factors in goaltender hip injuries; however, other factors like goalie equipment type (ie. size, stiffness/flexibility) may also exacerbate predisposed hip joints to injury.



Wijdicks et al.<sup>19</sup> investigated the effect of varying goal pad widths on goaltender hip kinematics and ground impact forces during butterfly movements. They observed that the hip flexion and abduction motions were within the goaltender's range of motion (ROM) limits, but their hips internally rotated to their passive limits. This study demonstrates that the butterfly save technique places the hips in compromising positions thought to increase the risk of injury. They also reported that goal pad width did not significantly affect goaltender hip kinematics; however, broken in goal pads required significantly less hip internal rotation compared to new goal pads of the same width. Unfortunately, this study did not report the butterfly width in these different pads; therefore, the decreased internal hip rotation may be confounded by a decrease in butterfly width. Further research is required to better understand the effect of various goal pad conditions on a goaltender's body kinematics and performance.

Kinematic marker sets often used in biomechanics, similar to that used by Wijdicks et al.,<sup>19</sup> quantify hip motions including flexion and abduction, but have been criticized for their inaccuracy at the extreme ranges of hip rotation. For example, Schulz and Kimmel<sup>15</sup> observed 28-41° less hip rotation when thigh clusters were used compared to a shank cluster only marker set. Errors are introduced with thigh clusters as they follow the soft tissues of the thigh not the femoral motions<sup>4</sup> (skin motion artefact<sup>17</sup>), and this becomes worse when markers are located proximally compared to distally on the thigh.<sup>20</sup> Therefore, the purpose of this paper was to create a new kinematic protocol that could be used when equipment prevents typical marker placements. We propose to use Schulz and Kimmel's method for quantifying hip internal rotation<sup>15</sup> to investigate the effects that goal pad stiffness and leg channel width have on ice hockey goaltender hip kinematics during the butterfly movement. It is expected that a stiff or tight goal pad will restrain the goaltender's leg, resulting in larger hip internal rotations during butterfly movements.

### 2.2.1 Purpose

There were three objectives for this research. The first was to develop and verify a kinematic marker set that quantifies hip kinematics of a goaltender when they are wearing goalie equipment. This novel marker system uses markers on the pelvis, greater

trochanter, lateral thigh and posterior leg/shank to reduce interference with goal equipment. We verified this marker system by directly comparing its hip rotations to rotations determined by commonly used anatomical landmarks (CAST<sup>3</sup>). Second, we used the newly developed marker set to describe goaltender hip kinematics while performing butterfly movements. In particular, we quantified how closely goaltenders approach their end ranges of motion for active and passive hip internal rotation in four goal pad conditions (two leg channel widths and two pad stiffness conditions). We hypothesized that goaltenders would exceed their active ROM and approach their passive ROM (within 5°) in each of the four goal pad conditions when conducting butterfly movements. Finally, we evaluated the relationship between hip internal rotation and butterfly width (performance). We hypothesized that hip internal rotation and butterfly width would be strongly correlated.

## 2.3 Methods

### 2.3.1 Subjects

The butterfly technique requires substantial player experience to be performed in a consistent manner; therefore, junior level goaltenders were recruited. 12 local male goaltenders ranging from 16-20 years of age and included 2 Ontario Hockey League (OHL) goaltenders, 6 junior B goaltenders and 4 junior C goaltenders (Table 2.1). None of the goaltenders had a known history of hip pathology or injury that would prevent them from performing butterfly movements. This project was approved by the University of Western Ontario Research Ethics Board, and all participants provided informed consent.

**Table 2.1: Participant demographics with the average weekly hours of ice time and age of control leg pad condition**

	Subject #	Age (years)	Junior hockey Experience (years)	Hours of ice time/week (hours)	Age of Control leg pads (years)
<b>Average</b>	12	18.83	2.75	5.00	1.48
<b>Standard Deviation</b>	N/A	1.27	1.29	1.76	1.30

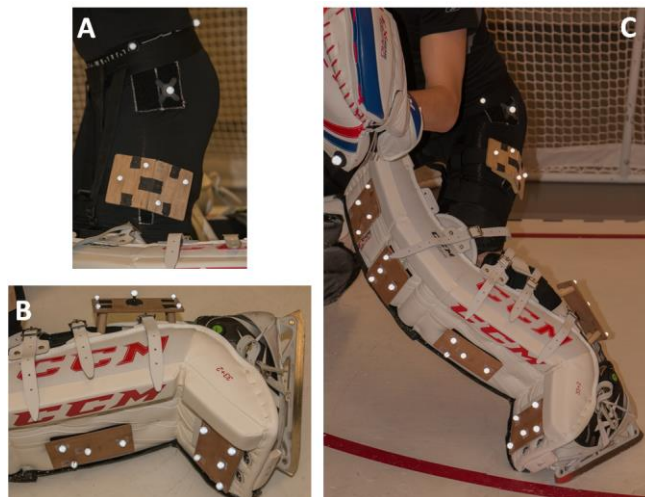
### 2.3.2 Hardware

Testing was performed using 10 infra-red motion capture cameras (Eagle, Motion Analysis Corp, CA, USA) recording markers on the goaltender's body and equipment at 60 Hz. A residual analysis of the goalie pad displacement data determined that the signal's frequency content was  $< 6$  Hz, and accordingly a 60 Hz frame rate was adequate. Goaltender movements were completed on a 3.4 m x 2.3 m synthetic ice surface with a regulation NHL goal crease in-lay (Eclipse Sports, Cambridge, ON). The surface was coated with a thin layer of lubricant (EZ Glide Enhancer, Eclipse Sports, Cambridge, ON) and custom covers (Figure 2.1C) were applied to the medial portion of the goalie leg pads to minimize friction.

### 2.3.3 Marker Sets

Two separate body marker sets were used in this study: the calibrated anatomical systems technique (CAST) was used as a reference marker set,<sup>3</sup> and a custom testing marker set. The markers located around the knee and ankle in the CAST marker set would be obscured by the goalie equipment, and therefore the testing marker set was developed to minimize marker loss and reduce interference with the goal equipment. This novel marker set uses four individual markers on the pelvis (right and left anterior superior iliac spine and posterior superior iliac spine) and one on the greater trochanter. In addition, two rigid marker clusters were located on the lateral thigh and posterior leg/shank (Figure 2.1). The leg/shank rigid marker cluster was placed approximately 5 cm off the back of the shank, allowing for improved tracking and for the goal pad straps to function and fit properly (figure 2.1B). These clusters were calibrated to their underlying anatomical structures using a standing reference trial that determined the relative orientation of the testing marker set and the CAST marker set. Anatomical coordinate systems of the pelvis, femur and tibia were determined using the International Society of Biomechanics (ISB) guidelines. Wijdicks et al.<sup>19</sup> reported that there was no

effect of leg dominance in butterfly movement. Therefore, hip kinematics were recorded on the left (glove hand) side.



**Figure 0.1:** The thigh rigid body was designed to strap and Velcro to the antero-lateral thigh with a Velcro patch beneath the rigid body and a strap that wrapped the thigh. Figure 2.1B: The leg rigid body was designed to sit off the posterior mid-calf and did not interfere with the goalie pads or straps. Figure 2.1C: Shows the location of the equipment marker set including markers on the thigh, leg, leg pads, skate, blocker and glove.

A goal equipment marker set was also constructed (Figure 2.1C). The equipment marker set consisted of markers on the gloves, skate and four rigid bodies located on the leg pads (thigh riser, knee, shin and toe). The skate marker cluster was used to identify the orientation and location of the foot.

#### 2.3.4 Testing Protocol

A standing reference trial was conducted prior to donning the goalie equipment to relate the testing marker set to the CAST marker set. The subjects then completed 15 body weight squats prior to testing their active and passive hip range of motion (ROM). Three active and passive ROM tests were completed to provide a reference point for the amount of achieved internal rotation during butterfly movements. ROM tests consisted of subjects standing on their right leg, with a balancing aid, and their left knee flexed to approximately 90°. The active test involved the subjects moving their hip in a circular pattern through their full range of flexion-extension and ab/adduction with their hip maximally internally rotated. The passive ROM test was similar, but a researcher controlled the hip motion and ensured that the subject's hip was maximally internally

rotated. Each subject's maximum internal rotation of the three trials was recorded for the active and passive ROM test. Hip motion during the ROM testing was collected using the passive motion capture system so it would be directly comparable with the motions achieved during the butterfly movement.

This study utilized a repeated measures protocol where goaltenders performed five full butterfly drop and recoveries in four different styles of goalie pad. Goaltenders were instructed to immediately recover from their butterfly using the technique of their choosing (single or double leg recovery); however, once decided, they had to use the same recovery technique for each of their butterflies. The four conditions of goalie pad style were: goalie's current set of goalie pads (Control), flexible wide leg channel (Flex-Wide), flexible tight leg channel (Flex-Tight) and stiff wide leg channel (Stiff-Wide). The testing condition order was randomized using a 4x4 Latin square design. Subjects wore goalie leg pads, knee guards, gloves and their own goalie skates for each trial. The testing marker set remained on the subjects throughout the entire testing protocol. Subjects were given five minutes prior to each testing condition to become comfortable with the synthetic ice and the pair of goalie pads.

Cortex software (4.1.2, Motion Analysis, Santa Rosa, CA) was used to capture and track the goaltender kinematic data. Each trial's data were then exported for post processing with a series of custom designed LabVIEW (2010, National Instruments, Austin, TX) programs to clip, filter (low-pass 4th order Butterworth filter with a cut-off of 6Hz, as determined using residual analysis) and calculate hip kinematics. Hip internal rotations were our primary objective, therefore hip internal rotations were calculated based on the orientation of the long axis of the tibia with respect to the pelvis marker set.<sup>15</sup> Unfortunately, hip flexion-extension and ab/adduction kinematics cannot be quantified using this method. Therefore, Euler sequences were used to determine these hip motions.<sup>15, 19, 7</sup>

The newly developed kinematic protocol was verified by comparing the hip joint kinematics derived from the CAST marker set (following the Euler sequence: Int/External rotation, flexion/extension then ab/adduction) to those from the testing

marker set during the three passive ROM tests. Root mean square (RMS) differences between the CAST and new marker set were calculated for each subject's hip flexion, abduction and internal rotation, then averaged across the group to identify the new marker set's validity. Reliability of the new marker set was evaluated by calculating a standard deviation of each subject's ROM test for hip flexion, abduction and rotation, then averaged across the group.

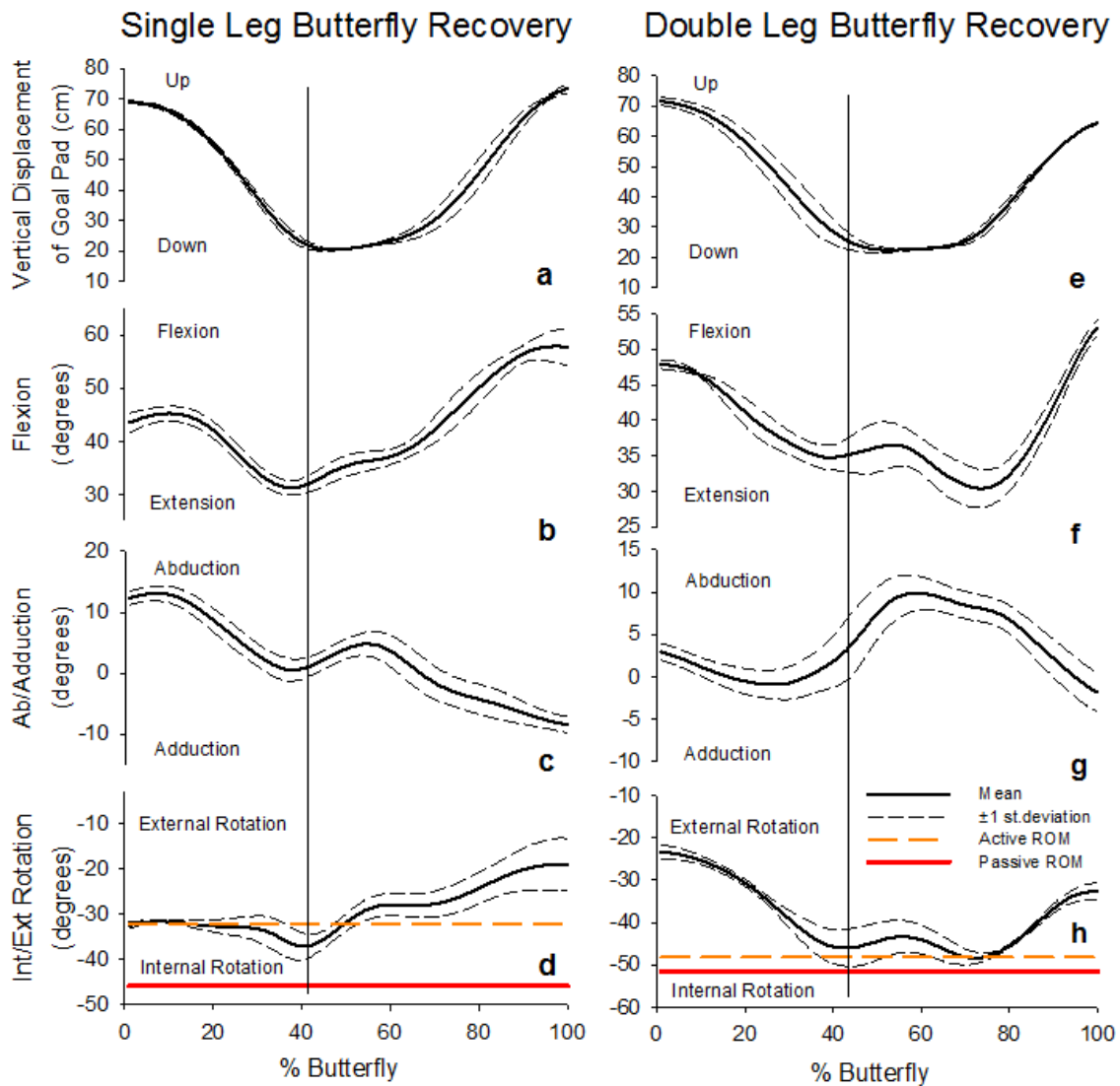
Hip kinematics during the butterfly movements were normalized to 100% of the butterfly movement (from the beginning of the butterfly drop to full recovery; Figure 2.2). Each subject's peak internal rotation value at ice contact was subtracted from their active ROM to indicate whether they approached or exceeded their ROM. As well, we estimated the butterfly width for each trial based on a half butterfly measure; this was calculated as the Y-axis difference (frontal plane) between the left ASIS marker and the 5<sup>th</sup> metatarsal marker.

Repeated-measure analysis of variance (ANOVA) tests were performed to determine whether there were significant differences in normalized hip internal rotation (goatender hip internal rotation with respect to their active ROM) and butterfly width in the four different pad conditions. When appropriate, differences between means were assessed using a Bonferroni post-hoc procedure. Finally, the average normalized peak internal rotation and average butterfly width were calculated for each pad condition to identify the overall relationship (correlation) between internal rotation and butterfly width.

## 2.4 Results

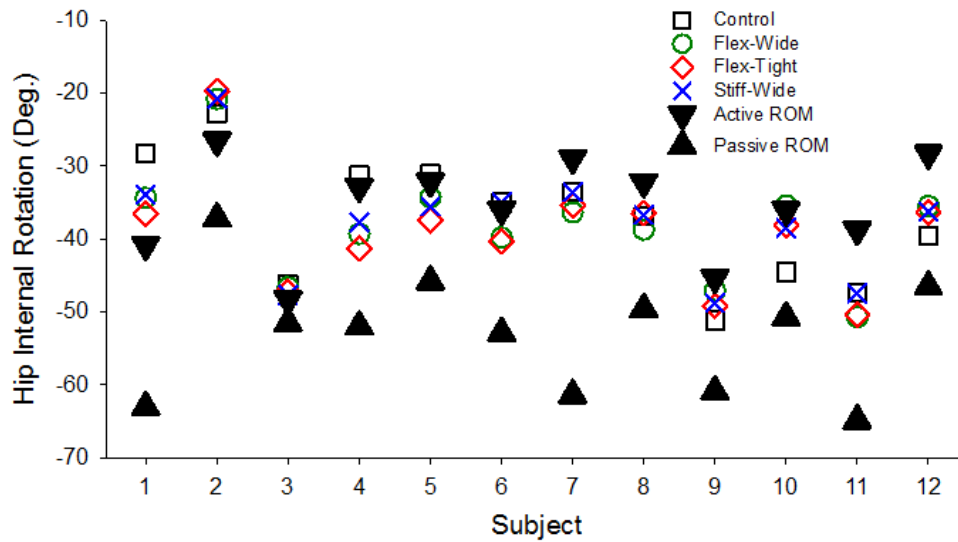
There was a strong concordance between the hip joint motions during the passive ROM motions with the CAST marker set and the new/modified testing marker set. The mean RMS differences and standard deviation, representing the new marker set's validity, for hip flexion/extension, ab/adduction and internal/external rotation were  $1.43^{\circ} (\pm 0.41^{\circ})$ ,  $1.0^{\circ} (\pm 0.39^{\circ})$  and  $3.32^{\circ} (\pm 1.32^{\circ})$ , respectively. The reliability values were  $0.32^{\circ}$ ,  $0.22^{\circ}$  and  $0.84^{\circ}$  for flexion/extension, ab/adduction and internal/external rotation, respectively. Hip kinematic curves for one representative subject performing the single

leg recovery (Figure 2.2a-d) and a different subject performing the double leg butterfly recovery technique (Figure 2.2e-h); depict the differences between the two techniques. Hip kinematic patterns were similar during the butterfly drop; however, during recovery, the kinematic patterns diverge. In particular, there is a large secondary internal rotation when goaltenders use the double leg butterfly recovery (Figure 2.2b).



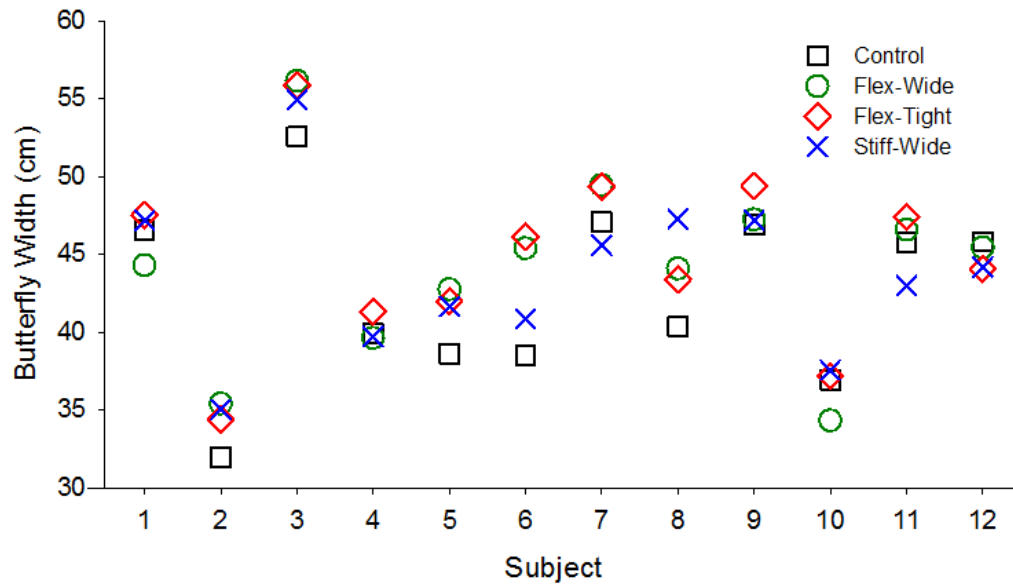
**Figure 0.2:** (Left; a-d) A representative goaltender's hip kinematic curves when performing a full butterfly with a single leg recovery (subject 5). (Right; e-h) A representative goaltender's hip kinematic curves when performing a full butterfly and a double leg recovery (subject 3). The solid curve is the mean, the dashed line is  $\pm 1$  standard deviation and the vertical solid line depicts the moment the goaltender's knee hit the ice.

Each subject showed relatively similar magnitudes of hip internal rotation for the different pad conditions (Figure 2.3). There was no significant main effect of goal pad condition on the amount of achieved hip internal rotation. There was, however, a significant main effect of goal pad condition on achieved butterfly width ( $P=0.022$ ; Figure 2.4). Post hoc comparisons revealed that the half butterfly width was significantly smaller in the control pad condition compared to the Flex-Tight pads (2.2cm;  $P=0.03$ ).

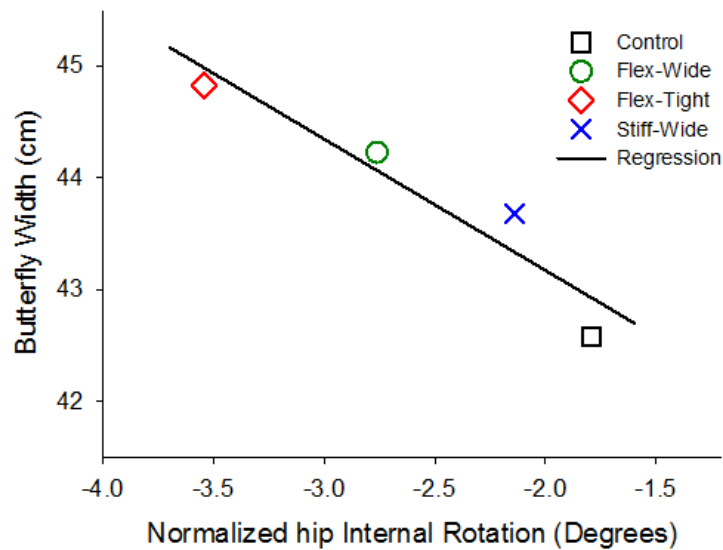


**Figure 0.3:** Each subject's average peak internal rotation in the four goalie pad conditions, with their active and passive ROM limits. Subjects are ordered from least to greatest internal rotation with respect to active ROM in the control goalie pad condition.





**Figure 0.4:** Each subject's butterfly width in the four goalie pad conditions. Subjects are ordered from least to greatest internal rotation with respect to active ROM in the control goalie pad condition.



**Figure 0.5:** Scatter plot of normalized hip internal rotation and butterfly width in the four goalie pad conditions. These variables are strongly correlated ( $r = -0.95$ ).

We observed an apparent relationship between normalized hip internal rotation and butterfly width ( $r = -0.95$ ), identifying that an increase in hip internal rotation is associated with an increase the butterfly width (Figure 2.5).

## 2.5 Discussion

There was a strong concordance between the CAST and testing marker sets during the ROM tests; there were relatively small RMS differences in hip flexion, abduction and rotation. The flexion and abduction motions had the lowest RMS differences ( $1.43^\circ$  and  $1.0^\circ$ , respectively). Hip internal rotations had the largest RMS difference ( $3.32^\circ$ ); however, each of these axes has a reliability of  $< 1^\circ$ . These results are an improvement on other kinematic marker sets,<sup>14, 15, 20</sup> likely because the modified testing marker set removes some of the skin motion artefact that plagues traditional gait marker sets.<sup>20</sup> Therefore, these relatively small validity and reliability numbers provided evidence that the new testing marker set was appropriate for quantifying ice hockey goaltender hip kinematics.

Hip kinematic patterns throughout the butterfly movement were similar to those observed by Wijdicks et al.<sup>19</sup> Goaltenders in their stance (ready) are flexed ( $\sim 70^\circ$ ), abducted ( $\sim 10^\circ$ ) and internally rotated ( $\sim 25\text{-}30^\circ$ ). It appears that some goaltenders choose to keep their knees closer together while in their stance position. This may help them remain balanced and prepared to move laterally. Common goaltender manoeuvres will apply high forces through the hip joint, and if the hip is already in a compromised flexed and internally rotated state (Figure 2.2), then the hip may be susceptible to injury.<sup>9</sup> From stance to the butterfly position, the hip extends, adducts and undergoes further internal rotation as their knees approach the ice (Figure 2.2). Hip extension enables the body to remain upright to ensure coverage of the upper half of the net, adduction closes the gap between the knees and internal rotation splays the ankles laterally to widen the butterfly. These hip kinematic motions during the butterfly drop were similar to those reported by Wijdicks et al.<sup>19</sup>

Large differences in hip kinematics were observed between the single and double leg recovery techniques (Figure 2.2). The majority of goaltenders use the single leg

recovery technique that allows the goaltender to remain laterally mobile throughout recovery; however, some goaltenders still use the double leg recovery technique. A single leg recovery has a slower rate of hip flexion (Figure 2.2b), while the double leg recovery involves rapid hip extension prior to hip flexion and the knees being lifted from the ice surface (Figure 2.2f). The abduction motion observed after ice contact indicates that there may be large contact forces driving the knees apart. Wijdicks et al.,<sup>19</sup> did not report hip kinematics after ice contact, but they did observe peak ground reaction forces of  $1.45 \pm 0.43$  times body weight when goaltenders drop into the butterfly. Therefore, the abduction motions we observed post ice contact are consistent with previous research. During recovery, both techniques involve hip adduction when goaltenders rise to their ready stance.

The two butterfly recovery techniques have similar hip rotation patterns (the hip remains in an internally rotated state throughout the entire movement). However, as the goaltender prepares to raise their knee off the ice, the hips undergo increased internal rotation (Figure 2.2d and 2.2h). This motion is larger in the goaltenders that performed the double leg recovery technique. This amount of internal rotation during the double leg recovery often surpassed the amount of internal rotation that occurs at initial ice contact (Figure 2.2h).

Peak hip internal rotations at ice contact were similar in magnitude but did not approach subject passive internal ROM limits to the same degree as those reported in the Wijdicks et al.<sup>19</sup> article. Therefore, we accept our hypothesis that goaltenders exceed their active hip internal rotation ROM during the butterfly movement, but reject our hypothesis that they approach their passive ROM limit. Kinematic marker sets that rely upon thigh rigid body clusters have difficulty assessing hip rotations at extreme ROM<sup>14</sup> and this may be the reason that goaltenders in the Wijdicks et al. study had hip internal rotations that were similar to their passive ROM limit.<sup>19</sup> Our approach, using the Schultz and Kimmel method,<sup>15</sup> showed that goaltenders appear to internally rotate beyond their active ROM but few come within  $10^\circ$  of their passive limit (Figure 2.3). However, if we consider how quickly a puck moves from side to side and the frequency of tipped shots, then goaltenders may have additional internal rotation during game and practice situations.

This may indicate that goaltenders are stretching their hip external rotators, perhaps eccentrically, during the butterfly movement. Future research should evaluate this mechanism by collecting electromyography of the hip external rotators. The butterfly movement may also be placing stresses on the passive tissues of a goaltender's hip and may even cause bone on bone contact. An internally rotated and flexed hip may result in an abutment of the femoral head-neck junction against the acetabular rim,<sup>9, 21, 13</sup> and this project has observed that goaltenders adopt this compromised position while they are performing butterfly movements. The repeated combination of compromised body positions and large transient forces are environmental factors that are believed to contribute to the high incidence rate of intra-articular hip injuries in goaltenders.<sup>13</sup>

In this study the majority of goaltenders exceeded their active hip internal rotation limit (50%, 66%, 75% and 66% for the control pad, Flex-Wide, Flex-Tight, and Stiff-Wide, respectively). There was no significant main effect of goalie pad condition on hip internal rotation, suggesting that goal pad selection does not influence the peak amount of achieved hip internal rotation. Our data suggests that there may be other variables at play. For example, it appears that inter-subject differences related to butterfly technique, hip morphology and butterfly performance are significant determinants of a goaltender's achieved hip internal rotation during the butterfly movement. Therefore, the tested goalie pads may not prevent overuse injuries, but future goalie pad modification should be tested for their effect on a goaltender's body and their performance. Understanding the interactions between goaltenders and their goal pads could be used to modify the goal equipment to improve performance, while ensuring that goaltenders don't increase their musculoskeletal demands.

The butterfly width analysis determined that goaltenders performed significantly wider butterflies in the Flex-Tight goal pad compared to the control condition. From a goaltender performance perspective this is an excellent outcome. Goaltenders are performing significantly wider butterflies without significantly increasing their hip internal rotation. However, this interpretation should be considered with caution since hip internal rotation and butterfly width were correlated ( $r= 0.95$ ). Therefore, we accept our second hypothesis; an increase in hip internal rotation strongly coincided with an increase

in butterfly width (Figure 2.5). Albeit, these changes were small;  $1.7^\circ$  for normalized hip internal rotation (from  $-1.8^\circ$  to  $-3.5^\circ$ ; which is within the range of measurement error) and 2.2 cm for butterfly width (from 42.6 cm to 44.8 cm). This magnitude of increase in hip internal rotation would not place this cohort of goaltenders at risk of reaching their passive hip internal rotation limit. Therefore, a 2.2 cm increase in butterfly width may be worth switching to a flexible-tight leg channel goal pad, when considering that a puck is only 2.54 cm in height and 7.62 cm in diameter.

A potential limitation of this work is the possibility that the goal pad conditions had a psychological effect. The novelty of the new goal equipment may have changed the goaltenders effort and consequently influenced their butterfly performance. This effect may explain the significant increase in hip internal rotation achieved in a new 27.9 cm pad compared to a broken in 27.9 cm pad, observed by Wijdicks et al.<sup>19</sup> Also, in order to maintain a controlled testing environment there were no hockey pucks involved and the movements were conducted on synthetic ice not real ice. Therefore, future research should investigate whether the large hip internal rotations recorded in the controlled lab environment would increase in game or game-like situations (that include shots, tipped shots, etc.).

Another potential limitation is using Schultz and Kimmel's method for quantifying hip internal rotations in a dynamic task. Wren et al.<sup>20</sup> report that this method may be susceptible to error when the knee deviates from  $90^\circ$ . Their sensitivity tests showed that the hip internal rotation angle changed by less than  $\pm 5^\circ$  when knee flexion angles were between  $65^\circ$  and  $105^\circ$ ; although the knee flexion angle during stance and in the butterfly is within this range, it may approach these limits at times. If a subject were to reach these limits, then combined error reported by Wren et al. ( $\pm 5^\circ$ <sup>20</sup>) and the RMS difference of  $3.32^\circ$  is still below the internal rotation error of other kinematic marker sets.<sup>15</sup> Therefore, the authors remain confident in their internal hip rotation results.

## 2.6 Conclusion

The newly created marker set matched well with the gold standard CAST anatomical reference frame. The verified marker set was successfully used to quantify hip

kinematics of goaltenders performing butterfly movements. Butterfly technique variability influences the amount of internal rotation achieved; however, on average, goaltenders exceed their active internal range of motion during the butterfly movement. During games or game-like situations this range of motion may increase due to the necessarily quick lateral movements. Therefore, this may leave goaltenders susceptible to hip injuries like femoroacetabular impingement. Goal pad stiffness and channel width did not significantly affect the peak amount of hip internal rotation during the butterfly; however, they did result in a significant increase in butterfly width between the Flex-Tight and control goal pad conditions. We observed that the hip internal rotation and butterfly width variables were related; an increase in hip internal rotation was associated with an increase in butterfly width. The results of this work indicate that additional factors, such as a goaltender's butterfly technique, underlying hip pathology and butterfly performance, may contribute to overuse injuries since the differences in goal pad styles that we tested did not lead to significant differences in hip internal rotation angles.

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## Chapter 3

### 3 Quantifying ice hockey goaltender leg pad kinematics and the effect that different leg pad styles have on performance

#### 3.1 Summary

This study investigated the motions of four different ice hockey goalie leg pads with respect to the goaltenders' legs during butterfly manoeuvres. It also quantified the peak vertical butterfly drop velocity in the four goal pad conditions. Twelve junior goaltenders, 16-20 years of age, performed five butterfly manoeuvres in each of the four leg pad conditions (Flexible-Tight leg channel, Flexible-Wide leg channel, Stiff-Wide leg channel and Control). All motions were performed on synthetic ice and recorded using 3D passive motion capture. The four pad conditions had similar kinematic patterns in the sagittal, frontal and transverse planes, except for the Stiff-Wide leg pad in the transverse plane. During the butterfly drop phase the Stiff-Wide leg pad achieved  $\sim 10^\circ$  more external rotation compared to the other leg pad conditions. Goaltenders had greater peak vertical butterfly drop velocity in the Flex-Tight (3.05 m/s) and the Flex-Wide (3.0 m/s) leg pad conditions compared to the control (2.82 m/s) leg pads. The testing approach and resulting baseline data have successfully identified differences between goaltender leg pads and will be useful for evaluating the performance of future leg pad models.

## 3.2 Introduction

The dynamic nature of ice hockey requires goaltenders to perform rapid lateral movements and react quickly to oncoming shots, all while wearing 15-20 kg of personal protective equipment (PPE). One of the most common goaltender save techniques is the butterfly<sup>2,14</sup>, which is characterized by a goaltender internally rotating their hips while kneeling to block the lower half of the net with their leg pads. National Hockey League (NHL) goaltenders perform this movement approximately 300 times per practice<sup>5</sup> and 34 ( $\pm 6$ ) per game<sup>2</sup>. Goaltender leg pads are designed to minimize impact forces, but modern pads are also developed to help maintain a goaltender's balance in the butterfly position and permit lateral movement while in the butterfly. However, these equipment developments were primarily concerned with improving performance, while complying with league regulations, and may not have considered how equipment affects the human body. One proposed approach for developing sport equipment states that the first steps should be understanding the biomechanical factors that impact, not only, sport performance but also injury<sup>13</sup>.

PPE that surrounds limbs reduces heat dissipation and significantly increases the cardiovascular and metabolic cost when participants perform incremental exercise<sup>12</sup>. For example, elite goaltenders lose  $2.9 \text{ L} \pm 0.2 \text{ L/h}$  of sweat in a practice<sup>10</sup>, which equates to approximately 3.6% of body mass for an 80 kg goaltender. This is detrimental because body water loss greater than 2% of body mass may impair power production<sup>4</sup>, endurance capacity<sup>7</sup> and cognitive ability<sup>9</sup>. Injuries also commonly occur in goaltenders<sup>6</sup>, presumably due to extreme hip motions during common goaltending manoeuvres such as the butterfly<sup>15,8,11</sup> and during aggressive braking following standing lateral movement<sup>14</sup>. These motions combined with underlying hip pathologies have been suggested to increase the likelihood of goaltender hip injuries<sup>14,8</sup>.

If goaltenders choose to avoid these movements to reduce their risk of injury, then it would likely impede their ability to perform their principal function of stopping hockey pucks<sup>14</sup>. Therefore, PPE modifications may present the most practical method for reducing their risk of injury without compromising performance. To date, little research

has investigated ice hockey goaltender equipment. Most goal pad innovations are the result of professional player feedback and have not been quantified to identify their effect on performance and on the goaltender's body. Consequently, there is a need to gain a baseline understanding of how equipment moves with respect to the goaltender's body so that future equipment modifications can be compared to previous leg pad models and ultimately enhance the understanding of the effect of leg pad design on performance and injury. Therefore, there were two main objectives of this research.

### 3.2.1 Purpose

The first objective was to quantify and describe the ranges of motion (ROM) between varying leg pad styles (ie. stiffness and leg channel width) with respect to the goaltenders' legs in the sagittal, frontal and transverse planes. The second was to analyze differences in peak vertical butterfly drop velocity in the varying pad conditions.

## 3.3 Methods

### 3.3.1 Participants

Twelve male junior goaltenders between 16-20 years of age participated including 4 junior C goaltenders, 6 junior B goaltenders and 2 Ontario Hockey League (OHL) goaltenders. All participants provided informed consent to the research protocol that was approved by the University of Western Ontario Research Ethics Board.

### 3.3.2 Hardware

Prior to testing, ten infra-red motion capture cameras (Eagle, Motion Analysis Corp, CA, USA) were calibrated, following Motion Analysis Corp guidelines, yielding an average 3D Residual marker error of  $0.56 \text{ mm} \pm 0.34 \text{ mm}$ . Cameras tracked markers on the goaltender's body and goal equipment at 60 Hz, while goaltenders performed butterfly manoeuvres. The movements were performed on a 3.4 m x 2.3 m synthetic ice surface with a regulation NHL goal crease in-lay (Eclipse Sports, Cambridge, ON). In an attempt to reduce friction, a thin layer of lubricant (EZ Glide Enhancer, Eclipse Sports, Cambridge, ON) was applied to the ice surface according to the manufacturer's

instructions, and custom pad covers were applied to the medial aspect of the goaltender leg pads (Figure 3.1).

### 3.3.3 Marker Sets

Two marker sets were used during data collection: a verified custom designed body marker set and a goaltender PPE marker set<sup>8</sup>. The custom body marker set consisted of four individual markers on the pelvis, another on the greater trochanter and two additional rigid marker clusters located on the lateral thigh and posterior leg/shank (Figure 3.1). The leg marker cluster was elevated 5 cm off the back of the leg so that it did not interfere with the goal pad straps (Figure 3.1). This arrangement improved tracking and decreased interference with the goal equipment. Each marker cluster was defined with respect to their associated anatomical structures by conducting a reference trial that quantified the origin and orientation of the custom body marker set to a body calibration marker set (calibrated anatomical systems technique)<sup>3</sup> that was removed during testing. International Society of Biomechanics (ISB) guidelines were used to determine the anatomical conventions for the pelvis, femur and tibia<sup>16</sup>.



**Figure 3.1:** Markers located on the left pad, gloves, pelvis, thigh and leg. The leg rigid body was elevated 5 cm off the back of the shank so that it did not interfere with the goal pad straps.

The goaltender PPE marker set (Figure 3.1) consisted of markers on the trapper (left glove), blocker (right glove) and left leg pad. The goaltender leg pad rigid bodies consisted of four unique rigid bodies located on the front the thigh riser, knee, shin and boot of the goal pad. Wijdicks et al.<sup>15</sup> found that leg dominance did not affect the butterfly movement. Therefore, goaltender PPE and body kinematics were only measured on the left side to minimize visual interference caused by the blocker and stick (all participants had their trapper located on their left hand). All leg pad rigid bodies were fastened to the leg pads using adhesive Velcro straps. The glove markers were fastened to the equipment using double-sided tape.

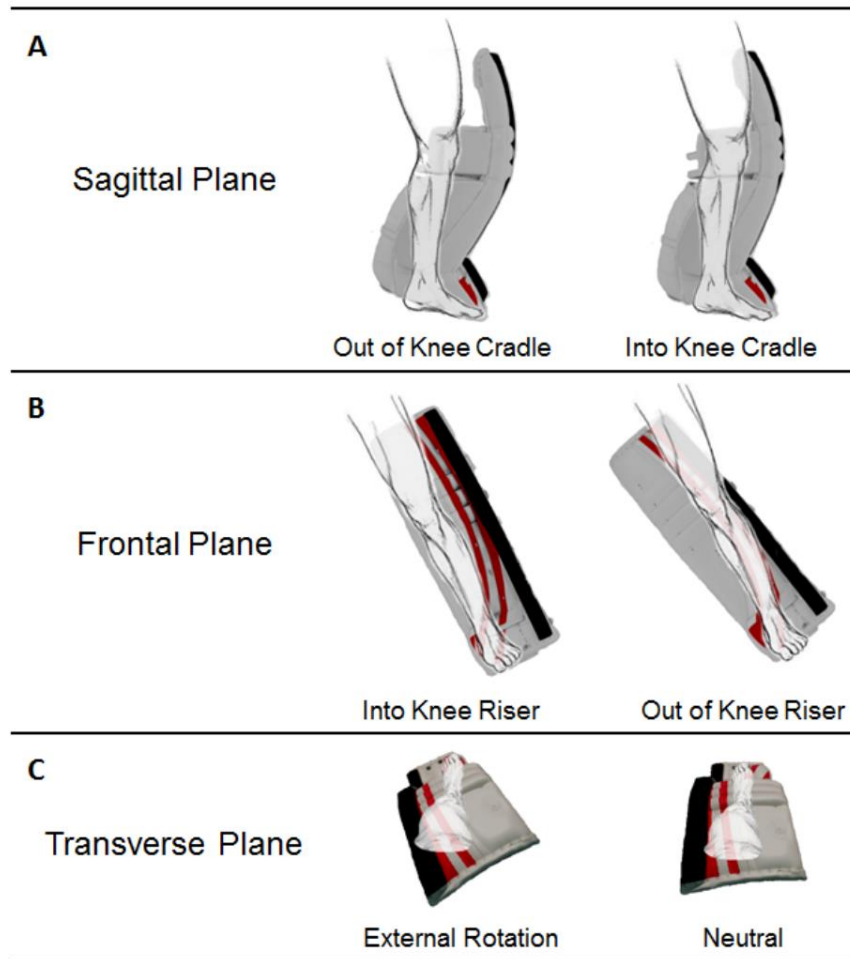
### 3.3.4 Testing Protocol

After the calibration reference trial, goaltenders performed 15 body weight squats as a dynamic warm up prior to donning the goaltender PPE. We used a repeated measures testing protocol where goaltenders performed five butterfly movements with recoveries in four different goal pad conditions. The condition presentation order was randomized using a balanced 4x4 Latin square design to minimize order effects.

The four conditions included a flexible tight leg channel (Flex-Tight), flexible wide leg channel (Flex-Wide), stiff wide leg channel (Stiff-Wide), and the goaltender's current pair of leg pads (Control). Participants wore their own goalie skates for all goal pad conditions. They wore a new pair of Reebok knee guards for the Flex-Tight, Flex-Wide and the Stiff-Wide goal pad conditions, and they wore their own knee guards during the Control condition. Prior to each goal pad condition, participants were given five minutes to become comfortable with the goal pad condition and synthetic ice.

Cortex software (4.1.2, Motion Analysis, Santa Rosa, CA) captured and tracked goaltender PPE and goaltender marker displacement data. Marker data were then exported for post processing using a series of custom designed LabVIEW (2010, National Instruments, Austin, TX) programs that clipped, filtered (low-pass fourth-order Butterworth filter with a cut-off of 6 Hz, as determined using residual analysis), and calculated the goal pad kinematics with respect to the goaltender's leg and butterfly drop velocity.

One of our objectives was to compare goaltender leg pad kinematics with respect to the leg. ROM throughout the entire butterfly movement was quantified to identify which style of pad had the largest movement with respect to the goaltenders' legs. Descriptive kinematic analyses divided the butterfly movement into two phases: butterfly drop (from initiation of butterfly drop to ice contact) and butterfly recovery (from ice contact to full recovery). This enabled a more detailed description of goal pad movement with respect to the goaltender's leg. The movement phases of the butterfly were distinguished using the displacement of the top lateral marker on the leg pads thigh section. This provided information about when the pad was dropping to the ice and when it had recovered to its initial stance position. The kinematic data were quantified according to rotations of the leg pads with respect to the leg in each of the anatomical planes. Sagittal plane motion described the anterior and posterior rotation of the pad with respect to the tibia (Figure 3.2A). Frontal plane motion described the medial-lateral rotation of the pad (Figure 3.2B) and transverse plane motion described the rotation of the pad around the long axis of the tibia (Figure 3.2C). The technical error of measurement for these rotations were  $0.58^\circ$ ,  $0.51^\circ$  and  $0.36^\circ$  for the sagittal plane, frontal plane and transverse plane rotations, respectively.



**Figure 3.2:** The scheme depicting the kinematic motions of the pad with respect to the goaltenders leg in each of the three planes of motion.

Each goaltender's kinematic data for the drop and recovery were time normalized to 100% and the five trials were averaged for each of the goal pad conditions. Overall ensemble average curves were created for each goal pad condition by combining the participant averages. Ranges of motion were used to describe the kinematics of the leg pads with respect to the goaltenders' leg, and peak vertical butterfly drop velocity depicted butterfly performance in the four pad conditions.

Vertical butterfly drop velocity was calculated as the peak of the first derivative of the vertical displacement of the uppermost-lateral marker on the thigh section of the goal pad with respect to time (Figure 3.1). A one-way repeated measures analysis of variance (ANOVA) was conducted to determine the statistical significance of the

differences in peak butterfly drop velocity ( $\alpha = 0.05$ ). One-way ANOVA tests were also performed to determine the statistical significance of the differences in goal pad ROM throughout the entire butterfly movement in the sagittal plane, frontal plane and the transverse plane ( $\alpha = 0.05$ ). To provide an estimate of effect size, partial eta squares were calculated for each of the ANOVAs. When significant main effects were detected, pairwise comparisons were conducted between pad conditions using the Bonferroni multiple comparison adjustment.

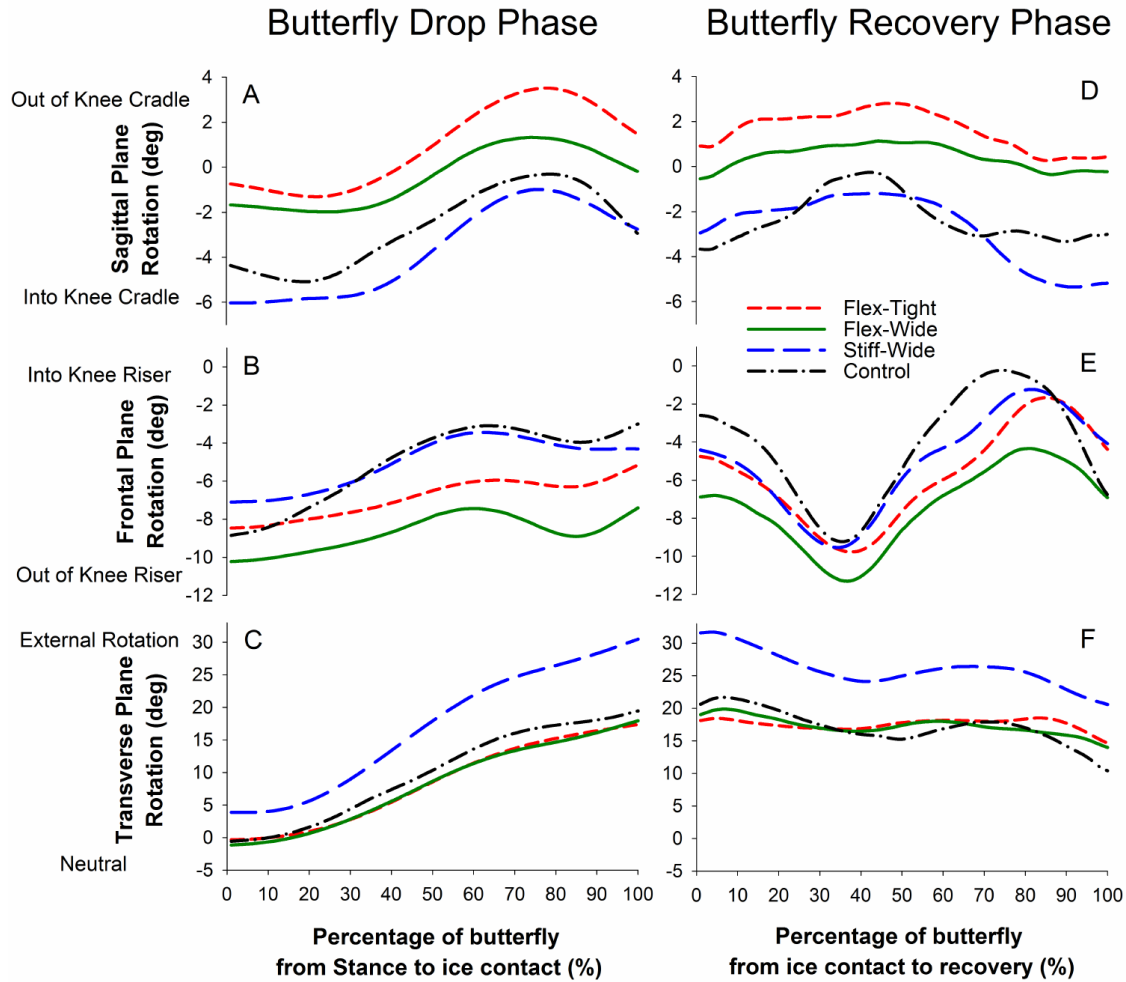
### 3.4 Results

There were no statistically significant differences in pad ROM in the sagittal and frontal plane. However, there was a significant effect of pad style on measures of transverse plane ROM ( $P = 0.003$ ,  $\eta_p^2 = 0.334$ ; Figure 3.4). Post-hoc comparisons revealed that the Stiff-Wide goal pad condition had significantly greater transverse plane ROM compared to the Flex-Tight ( $P=0.001$ ) and the Flex-Wide ( $P=0.005$ ) conditions.

The flexible and Control pad conditions started in a neutral position ( $0^\circ$ ) and externally rotated to angles of approximately  $18^\circ$  during the butterfly drop while the Stiff-Wide leg channel started  $5^\circ$  externally rotated and further rotated to  $30^\circ$  (Figure 3.3C). These larger rotations (approximately  $10^\circ$ ) in the Stiff-Wide condition continued throughout butterfly recovery. The Stiff-Wide pad started at  $30^\circ$  externally rotated and finished the recovery phase at  $20^\circ$ , while the other pad conditions started this phase at  $20^\circ$  externally rotated and finished at  $15^\circ$  (Figure 3.3F).

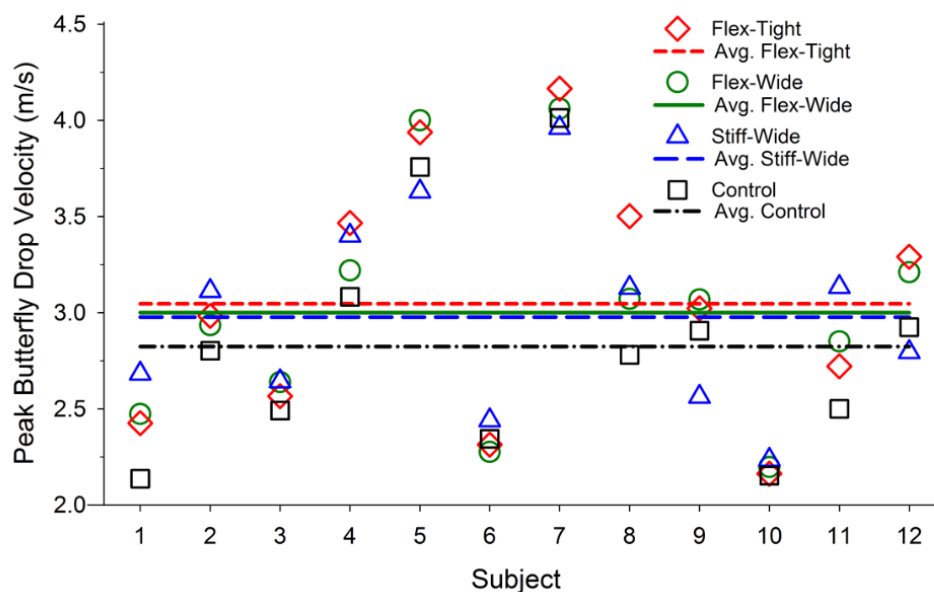
In general, the transverse plane had the largest relative rotations ( $18$ - $25^\circ$ ) while the frontal and sagittal plane rotations were smaller ( $6$ - $9^\circ$  and  $3$ - $5^\circ$  of rotation, respectively). In the frontal plane, the goaltender's knee moves toward the medial knee riser for the first 60% of the butterfly drop phase. In the sagittal plane, the goaltender's knee moves toward the front of the knee cradle for the initial 40% of the drop phase (Figure 3.3B and 3.3C). After these points, the goal pad moves away from the goaltender's knee until the conclusion of the butterfly drop (ie. ice contact). These patterns were reversed during the butterfly recovery phase.





**Figure 3.3:** Goal pad with respect to the goaltenders' leg in the four goal pad conditions during the butterfly drop (A-C) and butterfly recovery (D-F). Note that the graph panels have different scales between planes.

The mean peak butterfly drop velocities ( $\pm 1$  standard deviation) for the Flex-Tight, Flex-Wide, Stiff-Wide and control pad condition were  $3.05 (\pm 0.64 \text{ m/s})$ ,  $3.0 (\pm 0.59 \text{ m/s})$ ,  $2.98 (\pm 0.51 \text{ m/s})$ , and  $2.82 (\pm 0.58 \text{ m/s})$ , respectively. There was a significant main effect of goal pad condition on peak butterfly drop velocity ( $P = 0.014$ ,  $\eta_p^2 = 0.271$ ; Figure 3.4). Post-hoc comparisons revealed that peak butterfly drop velocities were significantly greater in the Flex-Tight ( $P = 0.018$ ; mean difference =  $0.22 \text{ m/s}$  with 95% confidence limits  $\pm 0.19 \text{ m/s}$ ) and Flex-Wide ( $P = 0.004$ ; mean difference =  $0.18 \text{ m/s}$  with 95% confidence limits  $\pm 0.12 \text{ m/s}$ ) condition compared to the control pad condition.



**Figure 3.4:** Each participant's average butterfly drop velocity in the four goal pad conditions. The horizontal lines indicate the group means for each of the goal pad conditions.

### 3.5 Discussion

There were few kinematic differences between pad conditions in each of the planes of motion; however, the Stiff-Wide condition achieved a significantly larger ROM in the transverse plane compared to the other conditions (approximately  $10^\circ$ ). This difference may be attributed to the wide leg channel in this condition. The Stiff-Wide goal pad condition had the widest leg channel of all the conditions, and accordingly there may have been less contact (friction) between the goaltender's leg and the leg channel/attachment straps allowing the pad to achieve a larger amount of external rotation.

External rotation of the pad during the butterfly drop phase is important because it turns the pad to face the approaching shot, subsequently protecting the goaltender's leg while in the butterfly. However, the large external rotation values observed in the Stiff-Wide condition may reflect that the pad is over rotating and is improperly aligned for oncoming shots. Over rotation may result in gaps below the leg pad while in the butterfly, particularly in the area above the knee because leg pads do not have medial leg

protection in this area. In terms of goaltender safety, over-rotation could potentially force the goaltender's lower body into an awkward posture in subsequent movements as they try to return the pad to a desirable position.

The leg pad motions in the sagittal and frontal planes were relatively small, but upon the start of movement the goaltender's knee stayed within the knee cradle (front) for the first 40% of butterfly drop, and moved toward the knee riser (medial) for the first 60% of butterfly drop. These motions of the knee into the knee cradle and knee riser initiate the downward trajectory of the goal pad. After contacting the knee cradle (sagittal plane) and the knee riser (frontal plane), the pad then appears to move away from the goaltender's knee in both planes. From a performance perspective this effect of the pad dropping to the ice quicker than the goaltender's leg is an intriguing trend that appears to be slightly more prominent in the wide leg channel conditions. However, it requires further investigation because it is not consistent with our peak butterfly drop velocity results, where the Flex-Tight condition achieved the largest butterfly drop velocity. We propose that this difference may be a result of an interaction between the goaltender's leg and the tight leg channel/straps making the Flex-Tight pads more responsive to the goaltender's motions compared to the wide channel pads. In the wide leg channel pads the goaltender needs to take up the slack between their leg and the pad channel/straps before the pads can initiate movement.

As with the butterfly drop phase, the butterfly recovery kinematics were similar for all leg pads in the sagittal and frontal planes, and had a small difference in the transverse plane. The conclusion of the butterfly recovery in the Stiff-Wide goal pad condition was more externally rotated than all other conditions; however, all conditions had a partial return to their pre-butterfly neutral position yet remained externally rotated at the moment of full recovery. This indicates that goal pads do not internally rotate back to their initial stance position during the recovery phase (Figure 3.3F at 100% compared to Figure 3.3C at 0%). Goaltenders often remedy this problem by pushing on the lateral side of their goal pads with their gloves to rotate them back into a neutral position. Therefore, there is an opportunity to incorporate a mechanism that will rotate the leg pads back into their

original location so that the goaltender does not have to move their gloves out of their stance position to manually reset the position of the pads.

The sagittal and frontal plane leg pad motions during butterfly recovery were the reverse of their respective butterfly drop phase kinematics but have larger magnitudes. During the first half of the butterfly recovery phase the goaltender's knee moves away from the knee cradle (Figure 3.3D) and knee riser (Figure 3.3C) then quickly returns once the goaltender nears complete recovery. The large ROM differences in the frontal plane between the butterfly drop (approximately 5° ROM: Figure 3.3B) and butterfly recovery phase (approximately 10° ROM Figure 3.3E) were likely the result of slack between the goaltender's leg and the attachment straps. During recovery tension in the attachment straps lift the pad upwards, however during the butterfly drop the stiff medial knee riser is used to push the pads toward the ice surface. The mobility and length of the pad attachment straps allow for the goal pad to move medially to a greater extent than laterally because the medial knee riser stops excessive lateral motion of the pad with respect to the leg. Therefore, it is likely that an increase in strap length will increase the frontal plane angles between the goaltender's leg and the goal pad during the butterfly recovery.

During the second half of the recovery phase the goal pad begins to return to its stance position in the sagittal and frontal planes. The goaltender's knee moves toward the knee cradle and the medial knee riser. When the goaltender is fully recovered and are back in their ready stance, the knee cradle rests against the front of the goaltender's knee and the medial knee riser falls slightly to the medial side (Figure 3.3A and B). This final medial resting position is expected because gravity pulls the pad toward the ice in the frontal plane.

The second purpose of this research was to quantify the peak butterfly drop velocities for the four goal pad conditions. The fastest goal pad condition, on average, was the Flex-Tight pad but was only 0.05 m/s faster than the Flex-Wide and 0.07 m/s faster than the Stiff-Wide goal pad. However, the Flex-Tight and the Flex-Wide goal pad conditions were the only pad conditions with significantly greater drop velocities than the

Control pad condition (Figure 3.4). It is difficult to determine the cause of these significant increases in peak butterfly drop velocity between the experimental goal pads and the control pads. The control goal pad condition included four different manufacturers and nine different styles of pad that varied in age (Mean  $\pm$  1 Standard deviation;  $1.56 \pm 1.26$  years). Therefore, these differences could be the result of a specific manufacturer's pad style or could be caused by goal pad wear. Stiffness in the boot region may decrease as goal pads break down. This would create a softer pivot point for the pad to rotate about because the inner foams of the boot region compress more easily during the butterfly drop phase. This may reduce the butterfly drop velocity, as observed in the current experiment, and could potentially decrease a goaltender's performance.

It has been suggested, in an attempt to reduce the risk of hip injury, that goaltenders should break in their goal pads because a broken-in goal pad requires significantly less hip internal rotation during the butterfly movement compared to a brand new goal pad of the same size<sup>15</sup>; however, they did not quantify butterfly width to ensure that performance was the same across all pad conditions. In contrast, Chapter 2, quantified both hip internal rotation and butterfly width performance<sup>8</sup> and did not observe any differences in hip internal rotation between goal pad conditions. However, there was a significant decrease in butterfly width performance in the control or worn goal pad condition (ie. goaltenders had tighter butterflies resulting in a smaller blocking surface with similar amounts of hip internal rotation). Chapter 2 also reported a strong positive correlation between hip internal rotation and butterfly width. Therefore, for a worn goalie pad to achieve the same butterfly width, goaltenders may have to increase their hip internal rotation. This provides additional evidence that there is an inverse relationship between health and performance for ice hockey goaltenders<sup>14</sup>.

The kinematic differences observed between Wijdicks et al.<sup>15</sup> and Frayne et al.<sup>8</sup> may be due to the use of different marker sets and varying types of goal pads in the Control condition. Therefore, additional research is necessary to evaluate the effect of goal pad wear on the goaltender's performance and body. For example, a longitudinal study that evaluates the mechanical properties and performance of goal pads over time would be useful for identifying the effect of goal pad wear on a goaltender's kinematics and performance.

Future research should also quantify forces at the equipment-goaltender interface. This would build upon this Chapter's kinematic analysis of the goal pad with respect to the goaltender's leg. Besides the transverse plane, there appear to be few kinematic differences between goal pad conditions; however, there may be force differences between conditions. The stiff goal pad condition may apply greater resistance to movements, consequently increasing the forces applied to the goaltender's body. An increase in force when goaltenders are in a compromised hip position, such as during the butterfly save technique<sup>8,15</sup>, may increase the risk of goaltenders developing intra-articular hip injuries<sup>11,1</sup>.

### 3.6 Conclusion

This project was the first to analyze the movement of ice hockey goaltender equipment with respect to the goaltender's body and it was an integral step toward understanding the interaction between a goaltender and their equipment. The different goal pads moved similarly, with the exception of the Stiff-Wide pad condition that had a significantly larger amount of external rotation compared to the other pad conditions. Goaltenders wearing the flexible pads, specifically the Flex-Tight and the Flex-Wide goal pad conditions, performed significantly faster butterfly drops compared to the Control pads. This may have been caused by differences in pad make and model for the Control pads, or could be due to equipment wear. The kinematic information obtained during this study provides goaltender PPE manufacturers with a baseline understanding of how goal pads move with respect to the goaltender's legs. It also provides key information about the motion of the pads during goaltender manoeuvres, highlighting the interaction between the goaltender's leg, pad straps and knee riser. Future goal pad modifications can then be tested and compared to this baseline to understand the modification's effect on goaltender performance. This will ensure that leg pads continue to advance and improve performance.

### 3.7 References

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## Chapter 4

### 4 Quantifying interface forces between goaltenders' legs and leg pads in ice hockey

#### 4.1 Summary

The development of sport equipment has evolved, through materials engineering, at a faster pace than biomechanical evaluations. This has created a gap in the study of biomechanical interactions between new equipment and the athlete. The objective of this research project was to develop and verify an equipment-goaltender interface force protocol to quantify the forces between a goaltender's leg and a goal pad while goaltenders perform butterfly movements. Using a testing apparatus that simulated butterfly drops from heights of 6.25 to 57.15 cm, interface forces were found to have 7.3% ( $\pm 5.5\%$ ) error. In order to quantify interface forces between goaltenders and their equipment, eight goaltenders performed 5 butterfly drops and recoveries on a synthetic ice surface in each butterfly condition (a flexible-tight and a stiff-wide goal pad condition). Peak interface forces were quantified at the medial, anterior and lateral areas of the goal pad during butterfly drop initiation, ice contact and recovery. There were no significant differences in peak force at any time during the butterfly movement or at any location on the goal pad. However, the flexible-tight goal pad condition had a larger peak medial force at ice contact compared to the stiff-wide goal pad condition ( $147.9 \pm 253.09$  N). Peak butterfly drop velocity analysis revealed that goaltenders were, on average, 0.16 m/s faster in the flexible-tight goal pad condition. Therefore, this difference in peak velocity may have contributed to the increase in peak medial contact force. During butterfly movements, these high contact forces combined with potentially injurious hip kinematics (abutment of the femoral head-neck junction against the acetabular rim) may increase a goaltender's risk of injury. Therefore, further understanding the biomechanical interactions between a goaltender's equipment and their body will help manufacturer's make educated decisions toward equipment modifications that minimize these hip kinematics and contact forces.

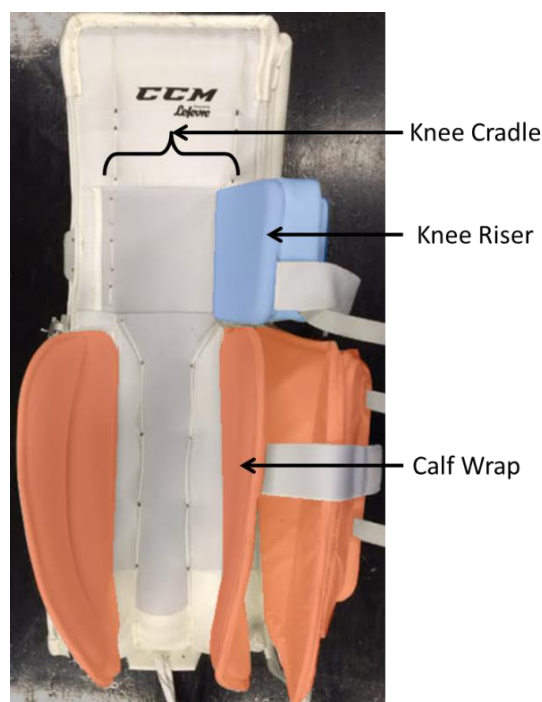
## 4.2 Introduction

With shots reaching velocities of 130 km/h<sup>8</sup>, personal protective equipment (PPE) is necessary to safeguard ice hockey goaltenders. Goalie equipment has been developed to decrease the impact forces from these shots and other hockey related contact. However, the effect of this equipment on the athlete's body is sometimes overlooked in the development process<sup>28</sup>. Wearing PPE can increase sweat rates<sup>21</sup>, cardiovascular and metabolic costs<sup>26</sup>, which could impair power production<sup>5</sup>, cognitive ability<sup>10</sup> and musculoskeletal demands<sup>4,27</sup>. In terms of musculoskeletal demands, PPE often decreases participants' range of motion<sup>4</sup>.

Goaltenders commonly adopt movements, such as the butterfly save technique<sup>30,9</sup>, that require large ROM and may be restricted by PPE. The butterfly requires goaltenders to drop to their knees while they flex and internally rotate their hips<sup>7</sup>. Chapter 2 identified that goaltenders often exceed their active hip internal rotation ROM, and approach their passive ROM during a butterfly manoeuvre<sup>9</sup>. Goaltenders perform these butterfly movements 34 ( $\pm 6$ ) times in a game<sup>2</sup> and approximately 300 times per practice<sup>6</sup>.

Wijdicks et al. report that the peak ground reaction force at butterfly ice contact, acting on one leg, is  $1155.9 \pm 317.5$  N<sup>30</sup>. These forces equate to  $1.45 \pm 0.43$  times body weight and are applied to the body when goaltenders are in a compromised body position (large hip internal rotation and flexion<sup>30,9</sup>). The combination of high contact forces and hip kinematics has been linked as a potential cause of intra-articular hip damage<sup>22</sup>. In fact, recent evidence has shown that goaltenders are more likely to suffer intra-articular hip damage (15%) compared to other hockey player positions (6.8% and 5.0% for defensemen and forwards, respectively<sup>7</sup>). With injury rates double that of other positional players, there is a clear need for kinetic analysis of common goaltender movements.

Wijdicks et al. quantified ground reaction forces between the ice surface and the goaltenders' leg pads<sup>30</sup>. These contact force estimates may not accurately represent the forces transmitting to the goaltenders' hip because the varying foams that make up the leg pad, in particular the medial knee riser (Figure 4.1), are likely modulating the transmitted forces. In a study quantifying soccer shin guard stud impact, peak forces at the stud-shin guard interface were approximately 10 times greater than the forces recorded beneath the shin guard at the shin guard-leg model interface<sup>1</sup>. Finite element analysis of this impact revealed that varying shin guard constructions altered the dispersion of contact forces<sup>1</sup>. Therefore, there is a need to develop a research protocol that quantifies interface forces between the goaltender's leg and the goal equipment. Pressure sensors located at the equipment-goaltender interface will provide a more accurate depiction of the forces being applied to the goaltenders body and represent an integral first step toward conducting a linked segment analysis for quantifying hip forces.



**Figure 4.1:** A posterior view of a stiff-wide goal pad. The knee cradle is the combination of the medial knee riser (blue), anterior foams and a lateral flap (not seen in this image but is a fixture on the Flex-Tight pads). The medial knee riser is constructed of a 1.27 cm thick layer of soft foam on the inside and approximately 3.81 cm thick dense foam on the outside. The calf wrap (orange) has medial and lateral foam flaps that wrap around the leg of the goaltender. There is also a built up medial region on the calf wrap that provides stability when the goaltender is in the butterfly position.

Quantifying equipment-goaltender interface forces will also provide greater insight into the interaction between goal pads and the goaltender's leg. Stefanyshyn et al.<sup>28</sup>, suggests that equipment has evolved, through materials engineering, at a faster pace than biomechanical evaluations. This has created a gap in the study of biomechanical interactions between new equipment and the athlete<sup>28</sup>. Therefore, identifying interface forces between the goal pad and the goaltender's leg throughout the entire butterfly

manoeuvre, and not only at ice contact, will advance the understanding of how goaltenders interact with their leg pads. Furthermore, it will build upon the kinematic analysis of the goal pad with respect to goaltenders' legs during the butterfly save technique, as presented in Chapter 3.

#### 4.2.1 Purpose

There were 3 objectives for this research. The first was to develop and verify a system that quantifies the interface forces between an ice hockey goaltender leg pad and a goaltender's leg. We hypothesize that the force data obtained from the pressure sensors will be highly correlated to the loads recorded above the goal pad medial knee riser and that peak ground reaction forces will be attenuated by the goal pads. The second objective was to apply the newly developed equipment-goaltender interface force protocol to quantify the medial, anterior and lateral peak forces during butterfly drop initiation, ice contact and recovery. Two leg pad conditions were studied: a stiff pad with a wide leg channel condition (Stiff-Wide) and a flexible pad with a tight leg channel condition (Flex-Tight). We hypothesized that the peak forces would be greater in the Stiff-Wide goal pad condition because the stiff construction may not attenuate the peak force to the same extent as the flexible pad. The third objective was to describe goal pad kinetics and the ways in which they apply force to goaltenders' legs during butterfly movements.

### 4.3 Verification Methods

#### 4.3.1 Verification Apparatus

A testing apparatus was created to represent the ice contact during the butterfly manoeuvre and was designed based on principles of other impact testing mechanisms<sup>16</sup>. This apparatus consisted of a reinforced 10.16 cm diameter PVC pipe, representing the goaltender's leg (leg model), attached to a single axis hinge located 15 cm from the goal pad boot (bottom). A load cell and effective mass were fastened to the leg model, which acted as a pendulum rotating about the hinge. Butterfly drops were simulated by releasing the leg model and goal pad from known heights (between 6.35 and 57.15 cm) onto a

Kistler force plate (Model 9287B, Kistler AG, Winterthur, Switzerland). The force plate was used to identify the external ground reaction forces at ice contact and to compare the contact forces to Wijdicks et al.<sup>30</sup>. The load cell (Omega 160, ATI Industrial Automation; Apex, NC, USA), mounted to the leg model at the approximate location of a goaltender's knee, recorded the contact forces that occurred above the medial knee riser of the goal pad. Masses (9.1 kg) were mounted to the top of the load cell to represent the effective mass of the goaltender's leg<sup>14, 12</sup> (Figure 4.2). Load cell forces were directly compared to the forces obtained from pressure sensors between the leg model and the leg pad for verification purposes.



**Figure 4.2:** Setup for pressure sensor verification. The testing mechanism with load cell and effective mass were placed within the leg channel of the goal pad and fastened using the goal pad leg straps.

Two pressure sensors were used to quantify the forces at the equipment-goaltender interface. A Tekscan CONFORMat sensor (Tekscan, Inc.; Boston, MA, USA) lined the leg channel of the goal pad from the top of the knee to the boot region. The sensor was attached using a custom made sensor sleeve with hook Velcro that affixed to loop Velcro lining of the goal pad (Figure 4.3). Pilot testing revealed that the CONFORMat sensor was saturating in the medial knee riser region during ice contact. Therefore, a second sensor (3200E, Tekscan, Inc.; Boston, MA, USA) was inserted

between the CONFORMat sensor and the internal side of the medial knee riser. This sensor has a larger capacity and could accommodate the high pressures that occur during the butterfly drop. The 3200E sensor was also attached using corresponding Velcro.



**Figure 4.3:** Left, view of a goal pad leg channel. Middle, the orange highlights depict the locations where loop Velcro was sewn into the leg channel to provide sensor attachment. Right, the custom sensor sleeve is attached to the loop velcro to minimize sensor shifting during goaltender movement. Note: the 3200E sensor is not visible in the right image because it is located below the top right region of the CONFORMat sensor (ie. the medial knee riser location).

The overall map of the interface pressures was generated by combining the output from the two sensors. The region of sensels (ie. individual sensors within the pressure sensor mats) on the CONFORMat sensor that overlapped with the 3200E pressure sensor (medial knee riser region) were digitally replaced, using custom LabVIEW program, with the 3200E pressure sensels. However, the 3200E sensor had a greater density of sensels compared to the CONFORMat sensor. The size of a 3 x 3 matrix of sensels in the 3200E sensor matched 1 sensel in the CONFORMat sensor. Therefore, the 3200E sensel density was decreased to match the CONFORMat sensel density, resulting in a total number of 1024 (32 by 32) sensels in the overall pressure sensor map. The pressure sensors were calibrated so that their output reflected contact force (described in the Testing Protocol section below).

The load cell forces, ground reaction forces (force plate) and the interface pressures were collected simultaneously during impact tests. The forces were sampled at

1000 Hz, and the pressures were sampled at the maximum possible rate (100 Hz). Residual analyses revealed that the signal content for all of these signals were less than 50 Hz, and accordingly these sample rates were adequate.

#### 4.3.2 Location of Sensels with respect to the pads

The location of the center of each sensel was digitized with respect to a common goal pad orientation (Origin: the inferior-lateral corner of the knee cradle, X-axis: anterior to posterior, Y-axis: along the longitudinal axis of the pad, Z-axis: medial to lateral), similar to that of the load cell, using an articulated 3D measurement system (MicroScribe G2X three-dimensional digitizer, Revware Inc, Raleigh, North Carolina). The MicroScribe has an average error of 0.239 mm with a standard deviation of 0.2 mm<sup>29</sup>.

Moulds were used to ensure that the orientation of the medial/lateral calf wrap, medial knee risers and straps of the goal pad were in a similar location to when a participant is wearing the pads. The moulds were created using “Big Gap” spray foam insulation (Great Stuff Big Gap Filler, The Dow Chemical Company, MI, USA) when a goaltender was wearing the goal pad. Once the foam had taken shape the goaltender’s leg was replaced with the verification leg model apparatus for final curing. The foam created a negative mould of the lateral and medial sides of the pad.

#### 4.3.3 Verification Protocol

The leg model, with load cell and effective mass, were placed within the goal pad leg channel and secured using the leg pad’s strap system. The testing apparatus was then released onto the force plate in a similar fashion to a goaltender performing a butterfly manoeuvre. Drop heights started at 6.35 cm and increased to 57.15 cm, in 6.35 cm increments. Two replicated drops were performed at each drop height for a total number of 18 drops.

Pressure sensor peak force magnitudes, in the Z-direction, were correlated to the load cell forces (Z-direction) to validate the accuracy of the pressure sensor protocol. A correlation threshold of  $r = 0.7$  was used to define adequate correlations between the

equipment-goaltender interface forces and the load cell forces. This threshold is described as “very large” in a review of statistics applied to sports medicine and exercise science<sup>13</sup>. An ideal relationship would have a slope of 1.0 and a Y-intercept of zero. This would indicate that the equipment interface forces are the same as the recorded load cell forces and as a result that the equipment-interface protocol is accurately quantifying the goal pad interface forces. Percent error was calculated between the interface forces and the load cell forces. Peak interface forces were also correlated to the force plate peak forces to estimate goal pad peak force attenuation.

#### 4.4 In vivo equipment-goaltender interface experiment

##### 4.4.1 Hardware

Testing was performed using a passive motion capture camera system (11 Eagle cameras; Motion Analysis Corp., Santa Rosa, CA) recording reflective rigid marker clusters located on the goaltender leg pads at 60 Hz. Residual Analysis revealed that the goalie pad’s displacement data had frequency content <6 Hz and accordingly the 60 Hz frame rate was sufficient. Reflective rigid marker clusters were placed on the front of the left goal pad at the thigh, knee, shin and boot region of the pad (Figure 4.4). There were also 3 individual markers located on the distal lateral section of both left and right leg pads in each goal pad condition.





**Figure 4.4:** Kinematic marker setup on the goal pad (Thigh, knee, shin and boot with 3 individual markers located on the distal lateral aspect of each the left and right leg pad. Passive motion capture cameras are visible at the top of the figure and the synthetic ice with the goal crease inlay, used to replicate on-ice conditions, is visible at the bottom of the figure. The kinematic markers located on the gloves were visual and only used for tracking orientation.

As with the verification mechanism, the CONFORMat and 3200E pressure sensors were placed within the left goal pad in each goal pad condition and recorded forces at 100 Hz. Wijdicks et al reported that there was no effect of leg dominance in the butterfly movement<sup>30</sup>; therefore, interface forces were only measured on one leg in both conditions. All goaltender butterfly movements were performed on a 3.4 X 2.3 m synthetic ice surface with a regulation NHL goal crease in-lay (Eclipse Sports, Cambridge ON, CAN). A thin layer of lubricant was placed on the synthetic ice surface and custom made medial goal pad covers were used to minimize friction and replicate on-ice conditions.

#### 4.4.2 Testing Protocol

Prior and immediately following testing, the pressure sensors were calibrated according to a user-defined calibration protocol<sup>3</sup>. The dual calibrations were conducted to account for any signal drift<sup>3</sup>. The Mark 10 force gauge (Series 5, Mark-10 Corporation, NY, USA), with a 103.25 cm<sup>2</sup> indenter tip, was applied to the medial knee riser section of the goal pad where the CONFORMat and the 3200E sensors overlapped. Time series force data from the Mark 10 were synchronized with the force data from the CONFORMat and the 3200E sensors. Scatter plots were constructed between the pressure data from each pressure sensor and the force Mark 10 data. A line of best fit was then calculated for each scatter plot to determine the calibration factor and intercept for each sensor. There was little drift between the prior and post calibrations and accordingly the calibration curves were an average of the prior and post calibration slopes and Y-intercept values. Therefore, all participants had unique pressure sensor calibration equations for each goal pad condition.

This study used a repeated-measures research protocol where 8 male goaltenders (ages 27-40) performed five full butterfly drops and recoveries in two different styles of goal pads, Flex-Tight and Stiff-Wide (Table 4.1). Goaltenders were instructed to immediately recover using a single leg recovery. Goal pad conditions were randomized between participants to minimize order effects. Subjects wore goaltender leg pads, knee guards (KPPRO Sr Knee protector Reebok), gloves and their own goalie skates for each trial. Subjects warmed up for five minutes prior to each testing condition to familiarize themselves with the ice surface and the goal pads.

**Table 4.1: Demographics table with weekly hours of ice time**

	Subject #	Age (years)	Height (cm)	Weight (kg)	Hours of ice time/week (hours)
<b>Average</b>	8	30.75	182.88	86.07	3.63
<b>Standard Deviation</b>	N/A	6.71	4.90	8.80	1.43

Cortex software (v 4.1.2; Motion Analysis Corp., Santa Rosa, CA) captured and tracked the goaltender kinematic data, and the pressure Sensor data was captured using CONFORMat Research software (v 7.1; Tekscan, Inc.; Boston, MA, USA). All data were exported for offline processing using custom designed LabVIEW (2010; National Instruments, Austin, TX) programs to synchronize, clip and filter the data. The equipment-goaltender interface forces were separated into three leg channel areas (medial, anterior and lateral) and analyzed over three phases of the butterfly movement (butterfly drop initiation, ice contact and butterfly recovery).

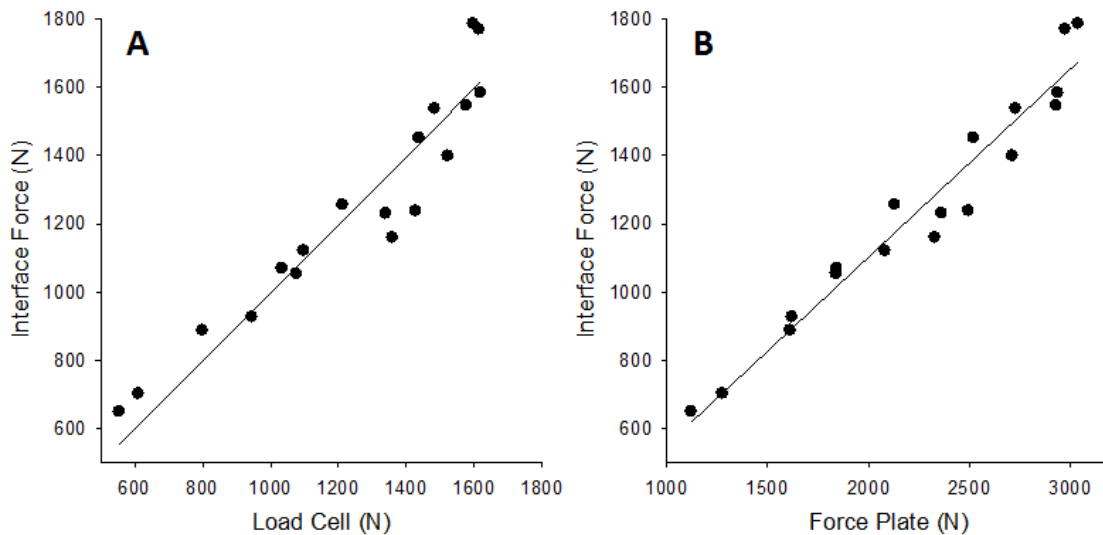
Peak medial, anterior and lateral forces were identified from each of the three phases of the butterfly manoeuvre. Nine paired T-tests were conducted to compare the two styles of pad (three phases of the butterfly and the three areas of the goal pad leg channel). A modified Bonferroni correction factor was applied to the alpha values <sup>11</sup> to decrease the probability of multiple comparison bias. Confidence intervals (CI), for each paired comparison, were adjusted according to their corresponding modified Bonferroni alpha value. Peak goal pad velocity was calculated during the butterfly drop and recovery phases (first derivative of the goal pad thigh rigid marker cluster). This was done to ensure that the interface forces were not confounded by performance. Paired T-tests, with Bonferroni corrections, were performed to identify differences in peak butterfly drop and recovery velocity between goal pad conditions.

## 4.5 Results

There was a very strong relationship between the peak interface forces and peak load cell forces during the verification protocol with a correlation of  $r = 0.95$ , and a linear relationship of  $y = 0.998x + 0$  (Figure 4.5A). There was an average percent error  $\pm 1$  Standard deviation (SD) of 7.3 ( $\pm 5.5$  %). The linear force relationship between the interface forces and the force plate during the verification protocol was  $y = 0.55x + 0$  (Figure 4.5B). This linear equation indicated that the goal pad attenuated peak ice contact force by approximately 45 %.

Paired comparisons revealed that there were no significant differences in force between the two pad conditions at any time during the butterfly movement (butterfly initiation, ice contact and butterfly recovery) or at any location on the goal pads (medial, anterior and lateral; Figure 4.6). The average peak butterfly drop and recovery velocities for the Flex-Tight and the Stiff-Wide conditions were  $2.9 (\pm 0.33 \text{ m/s})$  and  $2.74 (\pm 0.69 \text{ m/s})$ , and  $2.77 (\pm 0.33 \text{ m/s})$  and  $2.84 (\pm 0.62 \text{ m/s})$ , respectively. However, these differences were not statistically significant for peak butterfly drop ( $P = 0.17$ ) and recovery ( $P = 0.67$ ) velocity between the two pad conditions.

The equipment-goaltender interactions will be expressed using exemplary data of a subject wearing the stiff-wide goal pad condition (Figure 4.7) because there were no statistically significant differences in peak force. The force-time curve (Figure 4.7A) presents the peak forces in each butterfly phase. During butterfly initiation there were two peaks, with the largest peak force and force dispersion occurring on the anterior side of the pad (Figure 4.7A and C, respectively). The largest overall peak force occurred on the medial side during the instant the goaltender made contact with the ice (Figure 4.7A and G). The forces were much smaller during butterfly recovery; however, a lateral force occurred at the moment the goal pad began to lift from the ice surface (Figure 4.7A and H).



**Figure 4.5A:** Relationship between the load cell and the interface forces during verification testing ( $r = 0.95$  and a linear relationship of  $y = 0.998x$ ).

Figure 4.5B: Relationship between the force plate and the interface forces ( $y=0.55x$ ). This graph illustrates that the goal pads attenuated the peak ground reaction force by 45% during ice contact.

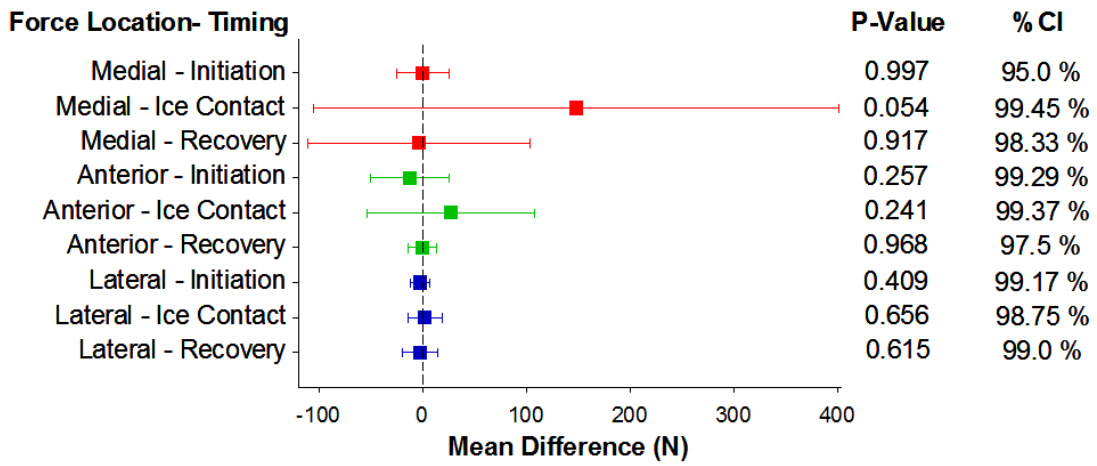
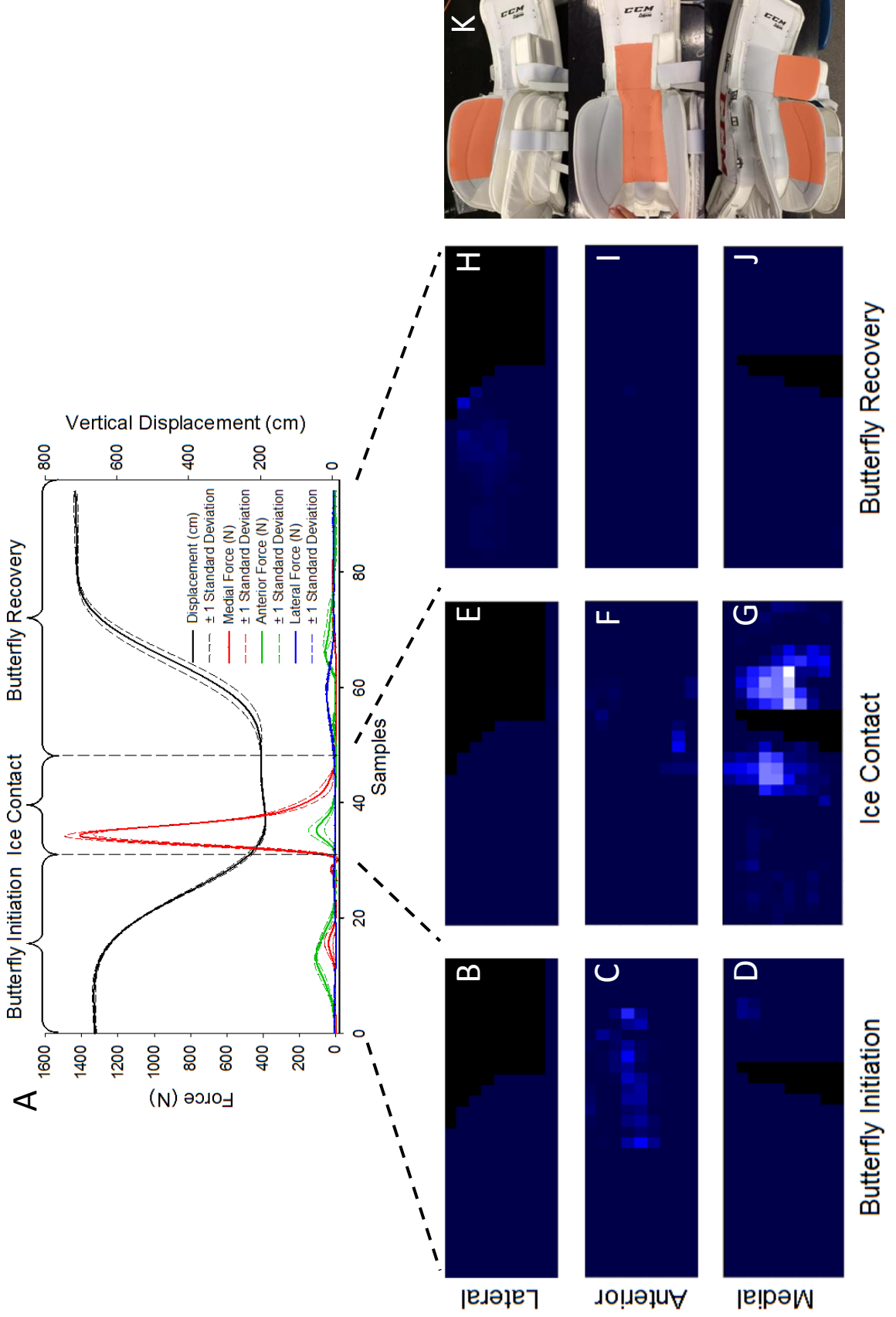


Figure 4.6: A forest plot of the mean differences, with adjusted confidence intervals (CI = whiskers), between the Flex-Tight and Stiff-Wide goal pad peak forces during the 3 phases of butterfly and on each of the 3 areas of the goal pad. Paired comparison P-values and the adjusted percent CI (adjusted based on modified Bonferroni) are also displayed. Note: a positive difference indicates that the Flex-Tight condition had a larger peak force compared to the Stiff-Wide goal pad condition.



**Figure 4.7:** A) Force-time ensemble average graph of the five butterfly movements performed by an exemplary subject wearing the Stiff-Wide condition. The average forces of each goal pad area (medial, anterior and lateral) over the entire butterfly movement, with vertical areas representing the three phases of the butterfly. The black line depicts the displacement of the top of the left goal pad. The nine intensity charts beneath the graph depict the dispersion of forces at the approximate moment of peak force during each phase of the butterfly (initiation B-D, ice contact E-G, and butterfly recovery H-J). The black area reflects void data as there was no sensel in that region, and the shade of blue qualitatively reflects the force magnitude. Dark blue = zero force, and gradients between light blue and white reflect increased force magnitude. Note: the three medial, anterior and lateral intensity charts correspond to the orange regions on the goal pad image (panel K).

## 4.6 Discussion

Verification tests revealed a strong concordance between the equipment-goaltender interface forces and the load cell data; the linear relationship had a slope of 0.998 with a y-intercept of 0. The correlation coefficient was  $r = 0.95$ , resulting in a coefficient of determination that was 90.3% ( $r^2 = 0.903$ ). This excellent relationship indicates that the interface forces explained 90.3% of the variance in the load cell data during verification testing. Therefore, the interface force protocol accurately reported the forces that occurred between goaltenders' legs and the goal pads.

In terms of the force attenuation properties of the goaltender leg pads, the linear relationship between the interface forces and the force plate during verification tests was  $y = 0.55x$ . This suggests that the goal pads had linear force-deformation properties that attenuated the peak ice contact force by approximately 45%. This amount of peak attenuation is larger than other studies that used similar impact velocities. For example, different models of hip protector PPE attenuate hip contact forces by an average of 19 to 26.8 % at the femoral neck<sup>16</sup>. One possible explanation for this difference is that the foams in the goal pad medial knee risers are much thicker than the hip protectors.

There were no significant differences in peak forces between the two goal pad conditions throughout the butterfly movement and at each location on the goal pads. The lack of significant differences in peak forces may be due to the similarity in leg channel construction between the two goal pad conditions. The goal pad conditions varied in

stiffness and leg channel width; however, the foam construction of the medial knee risers and the calf wraps were similar between conditions (Figure 4.1). Leg channel similarities may also explain why there were little differences in goal pad kinematics in the sagittal and frontal plane motions with respect to the goaltender's leg (Chapter 3).

Despite the knee riser and calf wrap similarities, there was a large difference in average force during ice contact on the medial side of the pad ( $147.9 \pm 253.09$  N), and a moderate difference on the anterior side ( $26.8 \pm 80.72$  N). These differences in peak force during ice contact may be confounded by differences in goaltender performance. The Flex-Tight pad condition had a peak butterfly drop velocity of 2.9 m/s and the Stiff-Wide condition was 2.74 m/s. Although these values were not significantly different from one another, the absolute difference may have resulted in the difference in peak force during ice contact.

Chapter 3 presented that there was a lack of significant differences in peak butterfly drop velocity between a Flex-Tight and a Stiff-Wide goal pad condition: 3.05 m/s in the Flex-Tight condition and 2.98 m/s in the Stiff-Wide condition. This 0.07 m/s difference is less than the 0.16 m/s difference observed in this study. However, the consistency of the greater peak velocity in the Flex-Tight condition in both studies indicates that there may be a performance advantage when wearing the Flex-Tight pad condition.

Wijdicks et al., report an overall average peak external ground reaction force 1155.9 ( $\pm 317.5$  N) from three different types of goal pads<sup>30</sup>. However, the current study reports that the average peak medial interface forces in the Flex-Tight and the Stiff-Wide goal pad conditions were 1221.8 ( $\pm 141.4$  N) and 1073.8 ( $\pm 128.8$  N), respectively. We observed that the external ground reaction forces were approximately 1.8 times greater than the interface forces during the verification test. Therefore, it is likely that the contact forces reported in the current study were considerably larger than those reported by Wijdicks et al.,<sup>30</sup>. These differences in peak contact force may be attributed to the different skill of the participants tested in each study and the different models of goal pads tested. The types of leg pads that were studied by Wijdicks et al., were from 2005



and did not have the same materials in the medial side of the pads. For example, the pads used in the current study used injection moulded foams<sup>17</sup> which are more rigid than older pad models and may result in larger transient forces at ice contact.

#### 4.6.1 Goaltender leg pad-Goaltender Interaction

##### 4.6.1.1 *Butterfly Initiation*

During the initiation of the butterfly movement the first and largest force occurs on the anterior portion of the pad as the goaltender drives their knee into the knee cradle initiating the downward trajectory of the leg pad. Following the initial anterior contact there is a small force on the medial side that may be the result of the goal pad externally rotating on the goaltender's leg as observed in Chapter 3. When the goaltender is approximately half way through the butterfly drop, the medial and anterior forces decrease. This may indicate that the goal pad may be dropping to the ice faster than the goaltender's leg. This effect of the pad moving faster than the leg is consistent with the kinematic observations in Chapter 3. The medial knee riser rotated away from the goaltender's knee in the frontal plane, and hence may of had a larger downward velocity than the goaltender's knee for the second half of the butterfly drop.

##### 4.6.1.2 *Ice Contact*

At the moment of ice contact, two forces occur: a large medial force and an anterior force. The medial ice contact force is the principal force throughout the entire butterfly movement due to the external rotation of the pad during the butterfly drop



**Figure 4.8:** Traditional boot strap setup (left) and the recent no boot strap setup (right pad) being adopted by the ice hockey goaltending community. Notice the position of the pads with respect to the skates between the strap setups. The pad in the no strap condition is sitting higher on the goaltender's leg. Figure was modified from <http://ingoalmag.com/news/power-to-push-new-ccm-extreme-flex-ii-boot-break/>.

(Chapter 3) and the downward momentum of the goaltender's body driving the pad into the ice. The medial ice contact forces are concentrated on the lower part of the medial knee riser and on the upper portion of the medial calf wrap (Figure 4.7). This may indicate that goaltenders are not landing on the center of the medial knee riser during butterfly movements.

The concentrated force on the lower half of the knee riser at ice contact suggests that the goal pads may be sliding up the goaltenders' legs during the butterfly drop phase. This "riding" up the leg may be the result of the recent trend in the ice hockey goaltending community, to omit boot straps (Figure 4.8). This option is intended to allow the pad to sit higher on the goaltender's leg during stance, resulting in a goaltender appearing larger to a shooter. However, if this strap setup results in goaltenders having a misaligned knee with respect to medial knee riser at ice contact, then there is a possibility that the goaltender's knee could slip off the medial knee riser and potentially contact the ice. This may be more likely to happen during fast lateral transitions made after quick passing or shot re-direction<sup>9</sup>. Falling off the medial knee riser has potential implications for injury because direct ice contact may result in forces that are approximately 1.81 times greater than landing on the medial knee riser (according to the verification testing; Figure 4.5B).

The peak anterior force at ice contact is approximately 10 % of the peak medial force; however, this force indicates that goaltenders are landing with their knee in contact with the anterior part of the knee cradle during controlled butterfly movements. A knee located deep or forward in the knee cradle will help maintain balance in the butterfly position.

#### 4.6.1.3 *Butterfly Recovery*

Similar to the ice contact phase, there are two forces that occur during the butterfly recovery phase. The first and most important force is the lateral force that initiates goal pad lift from the surface of the ice. The lateral recovery force begins when the leg pad is still on the ice and peaks early in the recovery phase. The force is generated as the goaltender lifts their leg and the lateral side of the lower leg makes contact with the

lateral calf wrap and the supporting top calf strap. The timing of the lateral force mirrors the kinematic findings in Chapter 3; the kinematic data suggests that the goaltender's leg rotates away from the medial knee riser (or toward the lateral side) for the first 30% of the butterfly recovery phase, and then the pad snaps upwards from the ice surface returning the knee to the center of the knee cradle. At this point the force on the lateral aspect of the pad decreases and an anterior force increases. This is an unexpected finding because the anterior force may be used to decelerate the pad and return it to its stance position. However, as reported in Chapter 3, the goal pad is externally rotated during this phase, and accordingly this anterior force may actually be directed vertically and may still be involved in the upwards recovery of the pad. In Chapter 3 all goal pad conditions maintained an externally rotated position on the goaltender's leg and this effect was the largest in the Stiff-Wide condition (approximately 20° externally rotated at full recovery). If this anterior force during butterfly recovery is contributing to the upwards motion of the pad, then it further supports the notion that the pads do not have a mechanism to internally rotate them back into their initial stance position (Chapter 3). This reinforces the possibility to develop a mechanism that will return the pads to their stance position, ensuring that goaltenders and their equipment are in position for subsequent shot attempts.

#### 4.6.2 Limitations/Future Directions

A limitation of this research is that the pressure sensors and corresponding attachment cables and cuffs made the goal pad heavier and bulky. Participants mentioned that it took a while to get used to the bulkiness and the weight difference between the instrumented (left pad) and non-instrumented goal pad (right pad). This added weight may have altered performance, but most importantly the addition of the pressure sensors within the leg channel would have made the leg channels tighter. As a result, the pressure sensors may have altered the interactions between the goal pads and the goaltender, particularly in the Flex-Tight condition due to the tightness of the leg channel. If the sensors made the channel tighter, then the tight leg condition may have artificially constrained the goal pad kinematics with respect to the goaltender's leg. This would have theoretically decreased goal pad motion. However, the pressure sensors with the custom

Velcro sleeve were the same thickness between each pad condition. Therefore, if there was a kinematic effect restricting goal pad motion in the Flex-Tight condition, then it should have been similar in the Stiff-Wide condition. Despite the decrease in leg channel width the successful implementation of the pressure sensor protocol opens other research opportunities.

In terms of future research directions, it would be interesting to conduct a linked segment mechanics analysis (LSM) using the equipment-goaltender interface force protocol to accurately quantify the applied forces to the body when goaltenders are performing the butterfly save technique. LSM is an inverse dynamics approach for calculating internal joint forces that occur within open chain mechanisms, like the human body, and is often used in biomechanics to assess joint reaction forces and moments in lower extremity joints<sup>31, 19, 25, 23</sup>. Applying the external forces recorded from the equipment-goaltender interface to anthropometric models and kinematic data, collected using the kinematic marker set developed in Chapter 1, will enable estimates of hip joint forces and moments when goaltenders perform the butterfly save technique.

Another promising future direction would be to investigate the effects of cumulative loading on goaltender's hips when they are performing butterfly movements during games and practices. Cumulative loading is a biomechanical approach that quantifies the accumulated load that soft tissues of a joint endure during physical activity<sup>18, 15</sup>. Cumulative loading has been quantified for lumbosacral joint<sup>15</sup> and metrics of cumulative load successfully distinguish between workers with low-back pain and those without pain<sup>20</sup>. These cumulative load metrics were poorly related to measures of peak spinal loading, and therefore cumulative load metrics are strong independent predictors of risk for low back pain. To the authors knowledge there has been little research that has specifically evaluated cumulative loading of the hip. Cumulative loading of the hip may fatigue the soft tissues of the hip, which may reduce the tissue's stress-bearing capacity and potentially decrease the joint's threshold for joint disorders<sup>15</sup>. Therefore, future goaltender research that focuses on the cumulative loading would provide a more detailed understanding of the total exposure of goaltender hip joint loading. It may be possible to adapt a published approach for estimating knee cumulative

loading<sup>24</sup>. For example, multiplying the average impulse of the medial ice contact force by the number of butterflies that a goaltender performs would provide a novel approach to estimating hip joint loading magnitude and frequency during butterfly movements

## 4.7 Conclusion

This research project successfully completed its three research objectives: to develop and verify a research protocol that quantifies equipment-goaltender interface forces, quantify medial, anterior and lateral peak forces in two goal pad conditions during butterfly drop initiation, ice contact and recovery, and lastly, describe how goaltender leg pads interact with goaltenders' legs during butterfly movements. The successful implementation of the equipment-goaltender interface force protocol provided an accurate measurement system for quantifying forces in the two leg pad conditions. No differences in peak force were observed at any goal pad location (medial, anterior or lateral) throughout any of the three butterfly phases (butterfly initiation, ice contact, and butterfly recovery); however, the interface force protocol did identify the way goaltenders manipulate their leg pads throughout the entire butterfly movement. This project provided a baseline understanding of the forces and the interactions between a goaltender's leg and their goal pads. Future goaltender leg pad development can now compare prototype leg pads to these data to ensure that equipment is both improving performance and safety. This type of testing sheds light on the biomechanical interactions between sport equipment and the athlete.

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## Chapter 5

### 5 Discussion

#### 5.1 Summary of Results/Implications

The overall objective of this thesis was to understand the effects of goaltender leg pads on goaltender safety and performance. Chapter 2 successfully developed and verified a new kinematic marker set that quantified ice hockey goaltender hip kinematics when wearing goaltender equipment and performing butterfly manoeuvres. Comparisons between the kinematic marker set and a common calibration marker set (CAST) determined that the RMS differences were  $<1^\circ$  for the hip flexion and abduction axis and  $3.32^\circ$  for hip internal rotation. Although the RMS difference for hip internal rotation was larger than the other axes, it was more accurate than other kinematic marker sets<sup>14, 15, 20</sup>. This improvement was likely because thigh skin motion artefact was decreased in the new kinematic marker set. Schulz and Kimmel<sup>15</sup> identified 28-41° less hip rotation when thigh clusters were used compared to a shank cluster marker set. Using a shank cluster marker set to study goaltender hip kinematics during butterfly manoeuvres revealed that hip internal rotation was not significantly different between goal pad conditions. This suggests that goal pad type does not change hip kinematics. This supports the point that the amount of achieved hip internal rotation during butterfly drops may be the result of underlying hip pathologies, butterfly technique and performance<sup>12</sup>.

Chapter 2 identified that goaltenders were fairly consistent when performing the butterfly save technique. On average 64% ( $\pm 10.4\%$ ) of goaltenders exceeded their active hip internal rotation ROM during butterfly movements. Those participants that exceeded their active ROM, consistently did so across goal pad conditions. Wijdicks et al., observed that all goaltenders reached their passive hip internal rotation limit during butterfly movements in all pad conditions<sup>19</sup>. The discrepancy in hip internal rotation ROM between Chapter 2 and Wijdicks et al. is likely due to skin motion<sup>16</sup> artefact and thigh rigid marker sets underestimating the actual amount of hip internal rotation<sup>15, 14</sup>.

The hip flexion and internal rotation kinematics during the butterfly movement (Chapter 2) indicate that goaltenders may be placing stress on the passive tissues of their hips and potentially causing abutment between the femoral head-neck junction and the acetabular rim<sup>6, 12, 7</sup>. Wyss et al. determined that the amount of hip internal rotation achieved during hip flexion is determined by bony structures<sup>21</sup>. Therefore, the butterfly manoeuvre<sup>19, 5</sup>, and its variants (VH and RVH), and specific skating motions (braking posterior to anterior)<sup>18</sup>, may result in bony impingement at the hip. Since these are common goaltender motions, they may explain why goaltenders have the highest percentage of cam-type femoroacetabular impingement (FAI) across all hockey player positions (approximate 87.6% versus 67.5% for forwards and defensemen<sup>8, 13</sup>). Philippon et al., suggest that underlying hip pathologies combined with the butterfly save technique may expose goaltenders to a higher risk of intra-articular hip injuries<sup>12</sup>.

Adjusting butterfly technique (ie. decrease butterfly width to decrease hip internal rotation: Chapter 2), or avoiding butterfly movements entirely, may reduce the risk of injury but would impede a goaltender's ability to stop hockey pucks<sup>18</sup>. Therefore, PPE modifications may present a practical method of decreasing injurious hip kinematics without compromising a goaltender's performance. Unfortunately, in Chapter 2 it was revealed that achieved hip internal rotation during butterfly manoeuvres was not significantly affected by pad type. The lack of statistically significant findings may be the result of the NHL rules and regulations<sup>17</sup> that control the size of goaltender leg pads. Most manufacturers build goal pads to the upper limit of the sizing specifications to provide the maximum blocking surface and leg protection to goaltenders. As a result, goal pads may be similar enough across manufacturers that they do not elicit hip kinematic differences. Therefore, if future goal pad modifications minimize injurious hip kinematics then they will have to be accepted by the NHL and implemented into their rules and regulations. This would be a difficult task to complete as it would take considerable political will to achieve and represents a fundamental paradigm shift to prioritize player safety.

Another objective of this thesis was to understand a goal pad's effect on goaltender performance. Chapter 2 revealed a performance difference (butterfly width)

between goal pads even though there was no statistically significant difference in hip kinematics. Therefore, understanding how various styles of goaltender leg pads move with respect to the goaltender's leg may provide insight into the cause of these performance differences.

Chapter 3 described goal pad kinematics (sagittal, frontal and transverse plane) with respect to the goaltender's leg in four goal pad conditions. It also quantified peak butterfly drop velocity to identify performance differences between leg pad conditions. There were no ROM differences in the sagittal or frontal plane; however, there was a significant difference in ROM in the transverse plane between goal pads. The similarities in the frontal and sagittal plane ROM across goal pad conditions are likely due to the similarities in goal pad construction (ie. medial knee riser and leg channel foams).

In contrast to the similarities in frontal and sagittal plane ROM across goal pad conditions, the Stiff-Wide goal pad condition had larger external rotations during the butterfly movement than the Flex-Tight and the Flex-Wide goal pad conditions. The Stiff-Wide goal pad condition had the widest leg channel of all the conditions; therefore, there may have been less contact (friction) between the goaltender's leg and the leg channel/attachment straps. This decreased friction may have permitted the pad to achieve larger external rotations during the butterfly. External rotation of a goal pad during the butterfly is very important because it turns the pad to face the approaching shot. However, very large external rotations, like that of the Stiff-Wide condition, may reflect pad over-rotation. As a result, the anterior surface of the pad may be facing upwards and be improperly aligned for oncoming shots. Unfortunately, this parameter was not quantified in Chapter 3, but is something that should be evaluated in future studies; over-rotation may result in gaps below the goal pads and could force the goaltender's lower body into awkward positions. These positions may potentially increase the goaltenders risk of lower body injuries during subsequent shot attempts.

Performance analysis revealed that peak butterfly drop velocities were significantly greater in the Flex-Tight and the Flex-Wide goal pad conditions compared to the control pad condition. Goal pad wear, combined with the fact that there were

different kinds (manufacturers) of goal pads in the control pad condition may have contributed to these differences in peak butterfly drop velocity. For example, certain kinds of goal pads have decreased stiffness in the boot region as they wear down. This may create a softer pivot point for the pad to rotate about. The inner foams of the boot region may compress more easily during the butterfly drop phase and ultimately reduce the butterfly drop velocity.

Interestingly, Chapters 2 and 3 revealed that the Flex-Tight goal pad condition had the largest butterfly width and the overall fastest butterfly drop velocity, respectively; however, goaltender hip kinematics and sagittal and frontal plane goal pad kinematics were not significantly different. Although there were not kinematic differences, there may have been kinetic effects that resulted in the Flex-Tight pad condition performance differences. In Chapter 4, a goaltender-equipment interface force research protocol was developed and verified. It was then used to quantify goal pad kinetics in a Flex-Tight and a Stiff-Wide goal pad condition. Peak butterfly drop and recovery velocities were also quantified to ensure that performance did not confound the recorded interface forces. There were no statistically significant differences in velocities between the two conditions; however, the Flex-Tight condition was the fastest with a mean difference of 0.16 m/s. The fact that the Flex-Tight condition consistently had greater performance values compared to the Stiff-Wide pad condition, suggests that there may be a systematic performance advantage to wearing the Flex-Tight pad condition.

Unfortunately, there were no significant differences in peak forces between the two pad conditions at any time during the butterfly movement or at any location. The lack of differences may have been the result of a relatively low number of participants (N=8), inconsistent butterfly performances within participants, and similarities in leg channel constructions between the different leg pads. As mentioned earlier, the medial knee riser and the calf wrap foams were similar between the goal pad conditions that were evaluated in this thesis. Although, there were no statistically significant differences in interface force, there were two interesting observations: the interface force patterns during butterfly recovery and the mean difference in medial peak force during ice contact.

During butterfly recovery there were two main forces. The first was a lateral force that initiated goal pad lift from the ice surface, then an anterior force toward the end of recovery. These interface forces mirror the kinematic findings in Chapter 3. The kinematic data suggests that for the first 30% of recovery the knee moves away from the medial knee riser and then the pad snaps upwards from the ice surface returning the knee to the center of the knee cradle. Chapter 4 describes that there is an anterior force toward the end of recovery after the initial lateral force begins to decrease. This anterior force could be interpreted as the pad decelerating as it returns to its stance position. However, Chapter 3 reported that goal pads are commonly externally rotated during the end of butterfly recovery. Accordingly, this anterior force may be directed vertically and may still be involved in lifting the pad upwards. If this anterior force during recovery is contributing to upwards motion then it further supports the notion, mentioned in Chapter 3, that goal pads do not have a mechanism to internally rotate them back into their initial stance position. Therefore there is a need to develop a mechanism that will return the pads to their neutral position.

The peak medial interface forces during ice contact revealed that the Flex-Tight goal pad condition had the greatest medial force ( $1221.8 \pm 141.4$  N). These values appear similar to those reported by Wijdicks et al.,  $1155.9 (\pm 317.5$  N)<sup>19</sup>; however, Wijdicks et al., reported external ground reaction forces between the goal pad and the ice surface. The verification tests presented in Chapter 3 showed that the forces between the goal pad and the ice surface were approximately 1.8 times greater than the forces occurring between the goaltender and the goal pad. This force difference suggests that the goal pads are attenuating the peak ice contact forces. Regardless of the goal pad peak force attenuation, goaltenders are applying force approximately 1.45 times body weight through each limb during butterfly drops<sup>19</sup>. These forces act on hips that are approaching the end of their range of motion and may cause intra-articular hip damage<sup>3</sup>. Therefore a more detailed analysis of goaltender hip kinetics is necessary to better understand the precise cause of intra-articular hip injuries in goaltenders.

## 5.2 Future Directions

Linked Segment Mechanics (LSM) is an inverse dynamics approach for calculating internal joint forces and is commonly used in biomechanics to assess joint reaction forces and moments. Combining the kinematic research protocol from Chapter 2 and the interface force protocol from Chapter 4 will allow for the estimation of hip joint forces and moments when goaltenders perform the butterfly save technique. LSM is the next logical progression to this particular line of ice hockey goaltender research. Future goal pad modifications can be tested to identify how the joint forces and moments are altered by the modification. This will help equipment manufacturers ensure that future pad modifications do not negatively influence goaltender hip joint forces and moments.

As mentioned earlier, underlying hip pathologies combined with the butterfly save technique may expose goaltenders to a higher risk of intra-articular hip injuries<sup>12</sup>. Therefore, there is a need to address goaltender hip injuries from more than just the perspective of equipment modification. For example, one alternative would be to monitor the number of butterfly movements a goaltender performs. This concept is similar to the pitch count for starting pitchers in baseball<sup>9</sup>. Ice hockey goaltenders, like pitchers, are a unique position in their respective sports. Pitchers are placing large forces on the medial aspect of their elbows<sup>11</sup> during every throw and as a result must be monitored in an attempt to minimize the risk of injury<sup>9</sup>. Perhaps goaltenders should be treated in the same way. This thesis has identified potentially damaging hip kinematics and high transient forces that are potentially leading to injury. Therefore, I propose that a butterfly count be implemented into goaltender training. Goaltenders are performing the butterfly more frequently in practices than in games (approximately 300 times in a practice<sup>2</sup> versus 34 ( $\pm 6$ ) times in a game<sup>1</sup>) and accordingly limits for practices may have a large impact. Monitoring and placing a butterfly repetition limit to goaltenders would decrease the number of times that goaltenders expose themselves to hip kinematics and large transient forces that can cause intra-articular injuries.

The implementation of a butterfly count hinges on first quantifying a butterfly limit. This could be conducted in two ways. A retrospective analysis of goaltender

injuries, potentially from the NCAA, <sup>4, 10</sup> could estimate the number of butterflies performed in a game <sup>1</sup> and in a practice <sup>2</sup>. This might indicate that goaltenders that have performed a larger number of butterfly drops may be at greater risk of hip injury. The second possibility of obtaining a butterfly limit would be to conduct a longitudinal study, following elite junior goaltenders, throughout their careers. It may be possible to develop wearable sensors, located close to the hip, that quantify the number of butterfly movements and modified butterfly movements (VH and RVH) performed by goaltenders. Then correlating the number of butterfly repetitions to goaltender injury history would provide an estimate of the number of butterflies that result in injury.

### 5.3 Conclusion

The overall objective of this thesis was to understand how ice hockey goaltender leg pads influence both the safety and performance of goaltenders. This thesis completed both of those objectives through the development, verification and application of a new kinematic marker set and a new equipment-goaltender interface force research protocol. The kinematic marker set enabled the measurement of goaltender's hip kinematics, and goal pad movements with respect to the goaltender's leg, when goaltenders performed butterfly movements. The interface force protocol quantified the applied forces from the goal pad to the goaltender's leg when goaltenders performed butterfly movements. The information obtained in this thesis has improved our understanding of goaltender hip kinematics, goal pad kinematics and kinetics with respect to the goaltender's body.

Chapter 2, identified that on average 64% of goaltenders exceeded their active internal rotation ROM limit during butterfly movements. Butterfly hip kinematics were not altered in the four different styles of goal pad (Chapter 2). However, in Chapter 2 and 3 performance differences were observed between the four goal pad conditions, suggesting that a flexible-tight goal pad will produce the fastest butterfly drop velocity and butterfly width without statistically altering hip kinematics. In Chapter 4, there were no interface force differences between a stiff-wide and a flexible-tight goal pad condition; however, peak medial ice contact forces averaged 1073.8 N and 1221.8 N, respectively. These ice contact forces combined with compromising hip kinematics may increase a

goaltender's risk of developing FAI. Unfortunately, the direct cause of goaltender intra-articular injuries remains unknown because it appears to have contributions from underlying hip pathologies, butterfly technique and performance. Controlling for hip pathologies would require pre-screening goaltenders, which would be difficult, but using equipment modifications to alter butterfly technique, without impeding performance, may be the best option for protecting goaltenders against hip injuries.

The high incidence rate of goaltender intra-articular hip injuries highlights the importance of pad design. Currently goal pad modifications are heavily based upon professional player feedback and traditional materials testing. However, the kinematic and interface force research protocols presented in this thesis directly quantify goal pad effects on a goaltender's body and performance. These approaches directly increase our understanding of the biomechanical interactions between new equipment modifications and the athlete. Accordingly these research protocols provide a quantitative approach to goaltender protective equipment testing that augments subjective measures of comfort and performance for future goal pad design. If hockey manufacturers adopt this approach for PPE testing, and the NHL regulations enable input, then it may be possible to reduce the likelihood of hip injuries in goaltenders while simultaneously optimizing performance.



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## 6 Appendices

### 6.1 Appendix A (Chapter 2 and 3 Ethics Approval)



Research Ethics

#### Use of Human Participants - Ethics Approval Notice

Principal Investigator: Dr. Jim Dickey  
 File Number: 103649  
 Review Level: Delegated  
 Approved Local Adult Participants: 15  
 Approved Local Minor Participants: 0  
 Protocol Title: Quantifying the effects that ice hockey goalie equipment has on the human body  
 Department & Institution: Health Sciences/Kinesiology, Western University  
 Sponsor:  
 Ethics Approval Date: July 10, 2013 Expiry Date: April 30, 2014  
 Documents Reviewed & Approved & Documents Received for Information:

Document Name	Comments	Version Date
Revised Letter of Information & Consent	Letter of Information _Participant	2013/07/09
Revised Letter of Information & Consent	Letter of Information _Caregiver	2013/07/09
Revised Western University Protocol	Adjusted Western Protocol	

This is to notify you that The University of Western Ontario Research Ethics Board for Health Sciences Research Involving Human Subjects (HSREB) which is organized and operates according to the Tri-Council Policy Statement: Ethical Conduct of Research Involving Humans and the Health Canada/CH Good Clinical Practice Practices: Consolidated Guidelines; and the applicable laws and regulations of Ontario has reviewed and granted approval to the above referenced revision(s) or amendment(s) on the approval date noted above. The membership of this REB also complies with the membership requirements for REB's as defined in Division 5 of the Food and Drug Regulations.

The ethics approval for this study shall remain valid until the expiry date noted above assuming timely and acceptable responses to the HSREB's periodic requests for surveillance and monitoring information. If you require an updated approval notice prior to that time you must request it using the University of Western Ontario Updated Approval Request Form.

Members of the HSREB who are named as investigators in research studies, or declare a conflict of interest, do not participate in discussion related to, nor vote on, such studies when they are presented to the HSREB.

The Chair of the HSREB is Dr. Joseph Gilbert. The HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 0000940.

Ethics Officer to Contact for Further Information

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## 6.2 Appendix B (Chapter 2 and 3 Ethics Revision)



Western  
Research

Research Ethics

### Western University Health Science Research Ethics Board HSREB Amendment Approval Notice

**Principal Investigator:** Dr. Jim Dickey  
**Department & Institution:** Health Sciences/Kinesiology, Western University

**HSREB File Number:** 103649  
**Study Title:** Quantifying the effects that ice hockey goalie equipment has on the human body  
**Sponsor:**

**HSREB Amendment Approval Date:** August 21, 2014  
**HSREB Expiry Date:** August 31, 2016

**Documents Approved and/or Received for Information:**

Document Name	Comments	Version Date
Revised Western University Protocol		2014/08/20

The Western University Health Science Research Ethics Board (HSREB) has reviewed and approved the amendment to the above named study, as of the HSREB Initial Approval Date noted above.

HSREB approval for this study remains valid until the HSREB Expiry Date noted above, conditional to timely submission and acceptance of HSREB Continuing Ethics Review. If an Updated Approval Notice is required prior to the HSREB Expiry Date, the Principal Investigator is responsible for completing and submitting an HSREB Updated Approval Form in a timely fashion.

The Western University HSREB operates in compliance with the Tri-Council Policy Statement Ethical Conduct for Research Involving Humans (TCPS2), the International Conference on Harmonization of Technical Requirements for Registration of Pharmaceuticals for Human Use Guideline for Good Clinical Practice Practices (ICH E6 R1), the Ontario Personal Health Information Protection Act (PHIPA, 2004), Part 4 of the Natural Health Product Regulations, Health Canada Medical Device Regulations and Part C, Division 5, of the Food and Drug Regulations of Health Canada.

Members of the HSREB who are named as Investigators in research studies do not participate in discussions related to, nor vote on such studies when they are presented to the REB.

The HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.



Ethics Officer to Contact for Further Information



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## 6.3 Appendix C (Chapter 4 Ethics Approval)



**Western  
Research**

Research Ethics

### Western University Health Science Research Ethics Board HSREB Delegated Initial Approval Notice

**Principal Investigator:** Dr. Jim Dickey  
**Department & Institution:** Health Sciences\Kinesiology, Western University

**Review Type:** Delegated  
**HSREB File Number:** 107487  
**Study Title:** Quantifying hip kinematics and kinetics in Ice hockey goaltenders  
**Sponsor:** Natural Sciences and Engineering Research Council

**HSREB Initial Approval Date:** January 9, 2016  
**HSREB Expiry Date:** January 09, 2017

**Documents Approved and/or Received for Information:**

Document Name	Comments	Version Date
Letter of Information & Consent		2016/01/06
Western University Protocol		2016/01/06
Recruitment Items	poster	2016/01/06

The Western University Health Science Research Ethics Board (HSREB) has reviewed and approved the above named study, as of the HSREB Initial Approval Date noted above.

HSREB approval for this study remains valid until the HSREB Expiry Date noted above, conditional to timely submission and acceptance of HSREB Continuing Ethics Review.

The Western University HSREB operates in compliance with the Tri-Council Policy Statement Ethical Conduct for Research Involving Humans (TCPS2), the International Conference on Harmonization of Technical Requirements for Registration of Pharmaceuticals for Human Use Guideline for Good Clinical Practice Practices (ICH E6 R1), the Ontario Personal Health Information Protection Act (PHIPA, 2004), Part 4 of the Natural Health Product Regulations, Health Canada Medical Device Regulations and Part C, Division 5, of the Food and Drug Regulations of Health Canada.

Members of the HSREB who are named as Investigators in research studies do not participate in discussions related to, nor vote on such studies when they are presented to the REB.

The HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.

Ethics Officer to Contact for Further Information

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## 6.4 Appendix D (Chapter 2 Figure Permissions)

5/9/2016

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**Title:** Development and Verification of a Protocol to Quantify Hip Joint Kinematics: An Evaluation of Ice Hockey Goaltender Pads on Hip Motion

**Author:** Ryan J. Frayne, Leila K. Kelleher, Peter K. Wegscheider, James P. Dickey

**Publication:** American Journal of Sports Medicine

**Publisher:** SAGE Publications

**Date:** 09/01/2015

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## Curriculum Vitae

**Ryan James Frayne MSc**

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Tel: [REDACTED]

PhD Candidate

Full Time: Yes

### 1. EDUCATION

<u>Degree</u>	<u>Institution</u>	<u>Faculty/Department</u>	<u>Date</u>
PhD	University of Western Ontario	Faculty of Health Sciences, Department of Kinesiology	2012-Present
MSc	University of Western Ontario	Faculty of Health Sciences, Department of Kinesiology	2008-2010
BScH	University of Guelph	Human Health and Nutritional Sciences, Human Kinetics	2003-2008

Phd Thesis: *The development of a standardized protocol that quantifies kinematic and kinetic effects of ice hockey goaltender equipment on the human body*

MSc Thesis: *Wear testing of a novel temporomandibular joint implant*

### 2. EMPLOYMENT HISTORY

<u>Rank/Position</u>	<u>Institution</u>	<u>Faculty/Department</u>	<u>Date</u>
Research Associate	University of Western Ontario	Faculty of Health Sciences	2010-2012
Research Assistant	University of Guelph	Human Health and Nutritional Sciences	May-August 2008

### 3. HONOURS AND AWARDS

#### Research Awards and Scholarships

<u>AWARD</u>	<u>INSTITUTION/ASSOCIATION</u>	<u>DATE</u>
3. Ontario Graduate Scholarship (PhD)	University of Western Ontario	2015-Present
2. Western Graduate Research Scholarship (PhD)	University of Western Ontario	2012-Present
1. Western Graduate Research Scholarship (MSc)	University of Western Ontario	2008-2010

### Teaching Awards

<u>AWARD</u>	<u>INSTITUTION/ASSOCIATION</u>	<u>DATE</u>
4. Course Instructor Award: Recognition of Excellence in Teaching	University of Western Ontario	2012
3. Teaching Assistant Award: Recognition of Outstanding Achievement in Teaching	University of Western Ontario	2009-2010
2. Teaching Assistant Award: Recognition of Excellence in Teaching	University of Western Ontario	2008-2009
1. Teaching Assistant Award: Award of Excellence	University of Western Ontario	2008-2009

### **4. TEACHING**

<u>ROLE/POSITION</u>	<u>INSTITUTION</u>	<u>FACULTY/DEPARTMENT</u>	<u>DATE</u>
6. Teaching Assistant	University of Western Ontario, Department of Kinesiology	KIN3341: Biomechanical Analysis of Physical Activity	2015
5. Teaching Assistant	University of Western Ontario, Department of Kinesiology	KIN4450B: Clinical Kinesiology	2009-2010, 2014
4. Course Instructor	University of Western Ontario, Department of Kinesiology	KIN4450B: Clinical Kinesiology	2012
3. Guest Lecturer	University of Western Ontario, Department of Kinesiology	KIN3341A: Biomechanical Analysis of Physical Activity	2011
2. Guest Lecturer	University of Western Ontario, Department of Kinesiology	9501RJF: Bioscience Graduate Seminar	2009, 2012, 2016
1. Teaching Assistant	University of Western Ontario, Department of Kinesiology	KIN2230A: Introductory Exercise Physiology	2008-2009

### **5. PUBLICATIONS**

Articles in Peer-reviewed Journals, Accepted/In Press:	5 (3 first author)
Articles in Peer-reviewed Journals, Under Review:	1 (1 first author)
Presentations at Professional Meetings:	10

#### PEER-REVIEWED JOURNAL ARTICLES, ACCEPTED/IN PRESS

5. **Frayne RJ**, Kelleher L, Wegscheider P, Dickey JP. Development and verification of a kinematic protocol to quantify hip joint kinematics: an evaluation of ice hockey goaltender pads on hip motion. *American Journal of Sports Medicine* 2015;43(9):2157-2163



4. **Frayne RJ**, Dean RB, Jenkyn TR. Improving ice hockey shot analysis using 3d optical motion capture; a pilot study determining the effects of a novel grip tape on slap shot performance. *Journal of Sports Engineering and Technology* 2015;229(2);136-144.
3. Dickey JP, Eger TR, **Frayne RJ**, Delgado GP, Ji X. Research using virtual reality: mining safety in the 21st century. *Minerals* 2013;3(2);145-164.
2. **Frayne RJ**, Dickey JP, Schwartz M. Wear testing of a novel temporomandibular joint implant. *Applied Bionics and Biomechanics* 2012;9(3);243-247.
1. Sacher N, **Frayne RJ**, Dickey JP. Investigating cervical muscle response and head kinematics during right, left, frontal and rear seated perturbation. *Traffic Injury Prevention* 2012;13(5);529-536.

#### PEER-REVIEWED JOURNAL ARTICLES, UNDER REVIEW

1. **Frayne RJ**, Dickey JP. Quantifying ice hockey goaltender leg pad kinematics and the effect that different leg pad styles have on performance. *Sports Engineering*. (Submitted March 2016).

#### PRESENTATIONS AT PROFESSIONAL MEETINGS

- Frayne RJ**, Harriss A, McRae S, Randhawa B, Dickey JP. Effect of ice hockey goaltender leg pad wear on Goaltender hip kinematics  
10. *Canadian Society of Biomechanics, Hamilton, ON, July 2016*
- Frayne RJ**, Dickey JP. Quantifying ice hockey goaltender leg pad kinematics and its effect on performance  
9. *International Society of Biomechanics Conference, Glasgow, Scotland, July 2015*.
- Frayne RJ**, Kelleher L, Wegsheider P, Dickey JP. Quantifying hip kinematics in ice hockey goaltenders.  
8. *The International Biomechanics Conference, Boston, MA, July 2014*  
7. *Faculty of Health Sciences Research Day, London, ON, April 2014*
- Frayne RJ**, Dickey JP. Testing tibio-femoral joint laxity throughout the gait cycle.  
6. *Faculty of Health Sciences Research Day, London, ON, April 2011*  
5. *Ontario Biomechanics Conference, Barrie, ON, March 2011*
- Frayne RJ**, Dickey JP, Schwartz M, Morphy G. Wear testing of a novel temporomandibular joint implant.  
4. *Canadian Society for Biomechanics, Kingston, ON, June 2010*  
3. *Ontario Biomechanics Conference, Barrie, ON, March 2010*

2. *Ontario Biomechanics Conference, Barrie, ON, March 2009*

**Frayne RJ**, Dickey JP, Thompson M, Mechefski C. Testing osseo-integrated prosthetics in load control.

1. *Human Health and Nutritional Sciences NSERC Research Day, Guelph, ON, August 2008*

## 6. FUNDING

3. *Quantification of ice hockey goaltender leg pad wear over a year of normal use, and their effect on goaltender body kinematics*

*Ontario Center of Excellence: TalentEdge Internship Program*

Industrial collaborator: Reebok-CCM hockey (Subsidiary of Adidas Group)

Funds awarded: \$104,514 (CAD) over 20 months (May 2015-January 2017)

2. Development of a standardized protocol that quantifies kinematic and kinetic effects of protective equipment on the human body

*Natural Sciences and Engineering Research Council of Canada: Collaborative Research and Development Grant*

Industrial collaborator: Reebok-CCM hockey (Subsidiary of Adidas Group)

Funds awarded: \$131,291 (CAD: January 2015- January 2017)

1. Development of a Standardized Testing Protocol that Quantifies the effect Protective Equipment has on the Human Body

*Natural Sciences and Engineering Research Council of Canada: Engage*

Industrial collaborator: Reebok-CCM hockey (Subsidiary of Adidas Group)

Funds Awarded: \$25,000 (CAD: May 2013-Oct 2013)

## 7. OTHER SCHOLARLY AND PROFESSIONAL ACTIVITIES

### KNOWLEDGE TRANSLATION

These are invited contributions to exchange knowledge between researchers, marketing teams, equipment developers, sales staff and the general public to increase awareness of my research and to support the efficiency of knowledge uptake and implementation into future product research and development.

<u>Type</u>	<u>Media Platform</u>	<u>Date</u>
12. TV Interview	<i>Rogers Cable TV</i>	March 28, 2016
11. TV Segment	<i>Discovery Channel (Daily Planet)</i>	February 24, 2016
10. Radio Interview	<i>CBC Kitchener/Waterloo</i>	February 23, 2016
9. Radio Interview	<i>CBC London</i>	February 22, 2016
8. Radio Interview	<i>610 CKTB Niagara Falls</i>	February 19, 2016

7. TV interview	<i>CTV News London</i>	February 18, 2016
6. Newspaper Interview	<i>London Free Press/National Post</i>	February 18, 2016
5. Newspaper/Camera interview	<i>Western University news</i>	February 1, 2016
4. Reebok-CCM Sales summit:	<i>Reebok-CCM Global Sales Summit meetings</i>	September 8-10, 2015
3. Promotional Video for CCM	<i>Reebok-CCM Sales summit and Online</i>	August 2015
2. Reebok-CCM Sales summit:	<i>Reebok-CCM Global Sales Summit meetings</i>	September 9-11, 2014
1. Promotional Video for CCM	<i>Reebok-CCM Sales summit and Online</i>	August 2014