Study of Soft Exoskeleton with Elastic Assistance on Ice Hockey Forward Skating Acceleration

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April 2018

A thesis submitted to McGill University in partial fulfillment of the requirements of the degree of Master of Science

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ABSTRACT

This Master's study examined the performance effects of a soft exoskeleton designed to store and return elastic energy about the hip joint during ice hockey skating starts. Three elastic resistance conditions ("Soft", "Medium", "Stiff") were examined. Kinematic, kinetic and perception data were collected on nine male high calibre hockey players during skating start accelerations over nine meters. This study demonstrated the feasibility of introducing soft exoskeletons to store and return elastic energy to an athlete's body while skating on ice. Several participants responded well, on average yielding 1.54% shorter times during skating start performance ($p=0.052$). Gross skating kinetic and kinematic patterns were unaltered, though reduced stride length and double support times were counter balanced by higher cadence. Based on individual time performance and preference measures, specific elastic resistances need to be tailored to each athlete in order to optimize their performance. Further study is warranted with larger sample sizes, both male and female athletes, longer familiarization periods, and on different skating tasks.

RÉSUMÉ

Cette maîtrise à examinée les effets de performance d'un exosquelette avec le but de retenir et redonner de l'énergie élastique au joint de l'hanche durant un accélération de départ-arrêté de hockey sur glace. Trois conditions de résistance élastique (souple, moyen et rigide) ont étés examiner. Des datas kinématique, kinétique et de perception ont étés collectionné sur neuf joueur de hockey de haut calibre pendant des accélérations de départ-arrêté sur neuf mètres. Ce projet démontre la faisabilité d'introduire des exosquelettes souple avec le but de retenir et redonner de l'énergie élastique au joint de l'hanche au corps de l'athlète durant le patinage sur la glace. Plusieurs participants ont bien réagi; en moyenne ils ont eu un rendement de vitesse de patinage de 1.54% plus vite ($p=0.052$). Les mouvements kinématique et kinétique n'ont pas changés, par contre la réduction de distance de pas et le temps de support double ont étés contre-balancés par une plus grande cadence. Basé sur les performances de temps et les mesures de préférences de chaque individuel, la résistance élastique a besoin d'être adapté différemment pour chaque athlète pour pouvoir optimiser leurs performance. D'autres études sont requis avec ces changements: des plus grandes échantillons, avec mâle et femelle, avec des périodes de familiarisation plus long et avec différentes type de mouvements de patinage.

ACKNOWLEDGEMENTS

I would like to thank Dr. David Pearsall first and foremost for the opportunities presented to me when I joined the Ice Hockey Research Group at McGill. Without your knowledge and guidance, I could not have succeeded in this project. You allowed me to figure problems out on my own, but were always there with inspiring ideas to encourage me to think outside the box.

I'd also like to thank Philippe Renaud our research assistant for all his help in the lab over the last two years, fielding my incessant questions about everything from particular MatLab scripts, to arguments over the best Adam Sandler movie. Phil, you truly made the lab environment a fun place to spend two years.

My colleagues in the IHRG are second to none. In no particular order, I'd like to thank Aiden Hallihan, Neil MacInnis, Dan Aponte, Dave Greencorn, Aleks Budarick, Mike Solomon, Dan Boucher and Kristie Liu for all of their support and friendship during my time at the lab. On top of their friendship, this group was invaluable in the process of data collection, and problem solving in all aspects of this master's project.

Acknowledgements are also due to Dr. Richard Preuss and Dr. Julie Côté who served on my advisory committee. As well as a big thank you to Dr. Shawn Robbins who was invaluable in the creation of data processing pipelines, and always had the answers to technical questions surrounding the motion capture protocol and statistical analyses.

Finally, I owe a huge debt of gratitude to my parents Gary and Sonia, my sister Liane, her husband Eric, and all of my great friends back home in Calgary for supporting me over the last two years. I love you all, and will never forget your encouraging words when things got tough, or your shared excitement in my successes throughout this endeavor. You're all the best!

CONTRIBUTION OF AUTHORS

Brian McPhee, the master's candidate was responsible for the experimental design as well as development of the system of elastic assistance to aid in the skating stride used in this study. Aside from these responsibilities the candidate was also in charge of experimental set up, data collection, analysis and the writing of this thesis, as well as other tasks associated with the completion of a master's thesis at McGill University. Numerous other individuals provided assistance to the completion of this study. David J. Pearsall, PhD, Associate Professor, Graduate Program Director, Department of Kinesiology and Physical Education, McGill University, the Candidate's supervisor played a critical role, actively advising on the experimental design and analysis. Richard Preuss, PhD, Assistant Professor, School of Physical and Occupational Therapy, McGill University, and Julie Côté, PhD, Associate Professor, Chair, Department of Kinesiology and Physical Education, McGill University, served on the candidate's advisory committee, and contributed to the experimental protocol. Shawn Robbins, PhD, Assistant Professor, School of Physical and Occupational Therapy, McGill University contributed to the development pipelines for the analysis of motion capture data, as well as advising statistical analysis methods.

Philippe Dixon, PhD, Research Fellow, T.H. Chan School of Public Health, Harvard University, helped in the development of data processing pipelines using the MatLab BioMech Zoo Toolbox used in data analysis. Tong Ching Tom Wu, PhD, Assistant Professor, Department of Movement Arts, Health Promotion and Leisure Studies, Bridgewater State University, provided ten motion capture cameras used during data collection. Phillippe Renaud, MSc, assisted with the data collection and analysis throughout the project. Finally, Daniel Aponte, PhD candidate, Aiden Hallihan, Kristie Liu, Michael Solomon, and Neil MacInnis, MSc candidates assisted in the data collection process.

INTRODUCTION

New integrated material and construction technology within sports equipment has become a large part of the sporting goods industry in recent years. In ice hockey manufacturing, the focus has been on hockey stick and skate construction techniques and the adoption of composite materials. It remains to be seen whether comparable advances can be seen in the apparel worn by hockey players. For example, apparel that can store elastic energy and work in parallel with the human body to augment movement patterns, are known as passive exoskeletons. These have shown promise when it comes to improving athletic performance, and reducing the metabolic cost associated with these movements (S. H. Collins, Wiggin, & Sawicki, 2015; Elliott, Sawicki, Marecki, & Herr, 2013a; Lee et al., 2017; W Van Dijk, van der Kooij, & Hekman, 2011a). However, not all individuals experience similar performance enhancement; for example, a study of elastic bands crossing the hip joint on vertical jump height found participant responses varied between elastic conditions (Wannop, Worobets, Madden, & Stefanyshyn, 2015).

In recent years a detailed kinematic understanding of ice hockey skating mechanics has been gained using 3-D motion capture technology employed on an ice surface (Budarick, 2017; Renaud, 2015; Shell, 2016). This has allowed researchers to identify the key movement patterns associated with maximal hockey skating starts (e.g. between high and low calibre skaters, as well as how sex differences affect the skating stride). These studies have confirmed the importance of explosive running in the first four acceleration strides in determining end maximal skating velocity. The constraints on greater power output is limited by the skaters' plyometric strength and constrained by rigid skate boots (Robert-Lachaine, Turcotte, Dixon, & Pearsall, 2012). Hence, the purpose of this study was to examine whether the former can be amplified by the use of a soft exoskeleton system to store elastic energy on each foot (skate) strike, and return it to the hip joint during push-off, aiding in skating acceleration. It is hypothesized that participants will see changes in their hip joint kinematics which will lead to improvements in their skating acceleration, however not every participant will achieve their peak performance under the same elastic condition.

REVIEW OF LITERATURE

This section will discuss previous research in fields related to this project. After a brief introduction about the history of skating, the biomechanics involved will be discussed: first with speed skating, and then with skating in ice hockey. How joint stiffness affects movement tasks and the potential of exoskeletons to augment human movement will be discussed. Together, these sections will present the rationale for this study.

History of skating

As humans have evolved, tool development has reduced physical burdens and increased work output. Quite often, when people think of this, they think of stone tools used for cutting and hunting. As important as these aspects of life were throughout human history, transportation was arguably of greater importance. To hunt successfully early humans needed to be able to follow herds of animals over long distances (Rodman & McHenry, 1980). In warm climates, this was easy, as walking is an incredibly efficient mode of transport (Massaad, Lejeune, & Detrembleur, 2007). However, in northern civilizations where snow and ice were yearly realities, walking long distances was not always the most efficient mode of transport. Skates first emerged over 3000 years ago in Europe (Formenti & Minetti, 2007). Made of long animal bone, and strapped to footwear with leather, these primitive skates hardly looked similar to the skates which athletes use today. These primitive skates did not have the edges associated with modern skate blades, and required the skater to use their upper body, and a stick to propel them across frozen lakes (Formenti & Minetti, 2007). Over the following millennia, skate technology gradually improved. By the 13th century, bones had been replaced by iron blades mounted to wooden platforms which could be attached to shoes. This advancement meant that skaters could make better use of their lower legs to propel them across ice. For 500 years, this design went through many iterations, changing its structure but relying on essentially the same construction of a metal blade attached to a wooden platform.

Skating originated as a leisure sport in the 17th century (Jos J De Koning, Houdijk, De Groot, & Bobbert, 2000). At this point in time athletes still relied on skates made of wood and metal fastened to footwear soles. The shift to competition skates put new demands on the construction of skates and skate technology. Design advancements included longer blades to reduce friction with the ice, and boots specifically built for skating. In the late 19th century, Axel Paulsen created a skate design for speed skating which lasted over 120 years, into the present era (Jos J De Koning et al., 2000). His design used a long steel runner fixed to the base of a leather boot with screws, this skate created the foundation for modern skate designs across all skating disciplines. Its design has changed rather little, being driven more by the advancement of materials and manufacturing than fundamental design changes. In the 1970's, manufacturers were still creating hockey skates from leather boots mated to a steel blade structure. In recent years, the development of skate technology has entered another era of advancement driven by the development of composite materials technology, and increased fundamental study of skating physiology and mechanics. Skates are now designed with three goals in mind: reducing weight, increasing protection and comfort, and improving stability (Robert-Lachaine et al., 2012). Skates of the modern era are designed exclusively for competition and leisure, where design focuses on performance and comfort above any other factors. Skates have also become more diverse, being designed differently in accordance with the demands of different skating applications.

Unlike skating which originated in Northern Europe, Ice Hockey is believed to have originated in Canada in the 1800s (Pearsall, Turcotte, & Murphy, 2000). Since the invention of the sport, it has seen growth to the international market. Hockey is now played by men, women, and children around the world.

Biomechanics of Skating

Speed Skating

The development of sports equipment to enhance performance strikes different sports at different times. A great example can be seen in long track speed skating where in new measurement techniques aided coaches in developing strategies and equipment to enhance athletes' performance. As a result, much of the existing literature on skating biomechanics focuses on the demands of speed skating. Although the motion patterns used in speed skating are not identical to hockey skating, the act of skating forward and around turns is common ground in both sports. When looking to understand the biomechanics of skating, this review will first examine the fundamental forces acting upon a skater.

Skating is an adaptation of normal locomotion created by different ground surface friction properties. Ice surface's low coefficient of friction (Jos J. de Koning, de Groot, & van Ingen Schenau, 1992) precludes effective push off forces parallel to the foot's long axis in the forward direction of travel. In skating, the blade affords a push off force that is applied perpendicular to foot's long axis at an angle to the intended direction of travel (J J de Koning, Thomas, Berger, de Groot, & van Ingen Schenau, 1995). Given that an ice surface between 0 and -10°C is deformable i.e. allows shallow channels to be scored into the ice surface by the narrow blades worn under the foot, the skate blade can obtain a lateral grip (or edge) with enough friction to push off. The blades combined low parallel friction and high perpendicular friction affords a prolonged gliding stance displacement. Further, unlike walking with a single fixed ground point in the stance phase, in skating the push off force is continuously applied as the skate stance glides in a forward then outward arc. The consecutive left and right skates' push offs occur at approximately 35 degrees to the forward line of progression. When skating in a straight line, push off force is at its greatest right before the leg reaches its peak extension (J J de Koning et al., 1987). This moment also coincides with the largest angle between the skate blade relative to the direction of travel. Conversely, when skating around a corner, force generation is relatively constant throughout the whole stride (J J de Koning et al., 1987).

The goal of speed skating is to sustain an optimal "speed" over a set distance in the lowest time. To identify an athlete's optimal speed much more has been studied in terms of skating technique parameters. For instance, de Koning et al. in 1987 found that skating speed is dependent upon two factors: how much force is applied with each skating stride, and the frequency of strides. It was seen that skating at higher speeds was not caused by an increase in force production, but by a decrease in stride duration (J J de Koning et al., 1987) or inversely at higher stride rates. The initial acceleration in speed skating at the start of a race resembles a transition from running to gliding. In this transition, stride time increases with each of the initial eight strides as the skate glides a further distance with each, and the skater accelerates (J J de Koning et al., 1995).

In the late 1980s, the traditional long track speed skate was replaced by a new design named the Klapskate. This new skate design utilized a hinge between the blade and skate boot located under the ball of the foot, which allowed athletes a greater degree of ankle plantarflexion during push off which had not been possible with traditional skates. The design was originally hypothesized to increase skating speed due to greater ankle joint force contributions (Jos J De Koning et al., 2000). However, the 5% increase in long track skating speed that resulted from these skates was later determined to be caused by the longer period of knee extension during push off. This allowed the knee extensors to apply force to the skating stride for an additional 50ms per stride (Houdijk et al., 2000). This additional period of knee extension led to an increase in work per stride of 25W, 15 W of this coming purely from the increased mechanical efficiency of the new skate design.

With the advanced measurement techniques, it is now possible to infer from inverse dynamics calculations the kinetic variables associated with skating mechanics (de Boer et al., 1987). Further, improvements in kinematic, kinetic and electromyography (EMG) measurement techniques have provided accurate and insightful description of the different joint contributions to power in a skating stride and how specific muscle activation patterns are recruited (de Boer et al., 1987; Jos J De Koning, De Groot, Jan, & Schenau, 1991; Houdijk et al., 2000). For instance it has been noted that skating utilizes a similar muscle recruitment pattern to what we see in vertical jumping, in that muscles follow a proximal to distal recruitment pattern. For example, muscles acting over the hip are activated first, followed by the knee joint then finally the ankle (Jos J De Koning et al., 1991). This muscle coordination pattern is seen in both beginner and expert speed skaters, suggesting that it does not require a long period of training.

While the biomechanics associated with speed skating are fairly well understood, they cannot all be translated directly to hockey skating. For example, in speed skating, the trunk is positioned close to horizontal in order to decrease aerodynamic drag, where as in hockey, skaters are much more upright in response to the added demands of stick handling and the physical nature of the game.

Hockey Skating

Skating is a fundamental skill in a game of hockey, upon which other skills (stick and puck control, checking) are developed (Pearsall et al., 2000); however hockey skating is fundamentally different from speed skating in a number of ways. In the game of hockey, a player can be expected to make repeated accelerations, interrupted by stops, changes of direction, and backwards skating, all while stick handling and being aware of other players on the ice. Because of the different tasks required, hockey players use specialized skates which share little in common with speed skates. Hockey skates are designed around three primary design criteria: to afford adequate support/stability to the skater's foot and ankle, to provide impact protection, and to be as light weight as possible (Robert-Lachaine et al., 2012; Turcotte, Renaud, Pearsall, Renaud, & Pearsall, 2015). Through these design goals, hockey skates have evolved to be different from speed skates in many ways. Unlike speed skating blades which are 1 mm wide, and about 400 mm long, flat with a single beveled edge; hockey skate blades are 3 mm wide to allow a central "hollow" in the blade with two outer edges, and have a curve from front to back called "rocker" (Pearsall et al., 2000). These two curvatures in the blade allow the skate to be more maneuverable, and to sharply dig or "bite" into the ice during stops and quick accelerations. Hence, ice hockey differs from speed skating not only in the equipment and skating mechanics.

Quantifying the mechanics of hockey skating is logistically difficult. Before the advancement of 3D motion capture allowed the technology to be utilized on an ice surface (Renaud et al., 2017), alternate environments were often used to gather data. For example, 2D and 3D video analysis have been used to capture the motions constrained to a skating treadmill (Chang, Turcotte, & Pearsall, 2009; Nobes et al., 2003; Upjohn, Turcotte, Pearsall, & Loh, 2008). While these treadmill tests allowed the quantification of lower body kinematic data, they lacked external validity. Recently, 3D body motion studies allowed in situ measurement on the ice surface (Renaud et al., 2017; Shell, 2016). For example, Renaud et al. (2017) were able to track body 3D Centre of Mass (CoM) movement during forward skate sprint starts. With this measurement approach, Functional acceleration differences were found between skill groups. High and low calibre skaters showed similar knee and hip extension and stride widths, high caliber skaters achieved higher CoM "running" vertical displacement than low caliber skaters (by 5 to 7 cm) that afforded long stride lengths, and hence greater start speeds. In situ, on-ice 3D kinematics has also been utilized evaluate the skate start mechanics of male and female elite level players (Shell, 2016). The main technique differences found were 10^{o} greater hip abduction at stride push-offs in males than females. Females also presented greater momentary knee extension pauses following skate contact with the ice. It was speculated that this could be a protective mechanism against medial (valgus) knee collapse in females.

Joint Stiffness

Within the context of this project to create a soft exoskeleton utilizing the properties of elastic energy storage and return to augment athletic performance, joint stiffness must be considered. The current literature on leg stiffness can be confusing, in that there are three terms used interchangeably: Joint Stiffness, Leg Stiffness and Vertical Stiffness (Brughelli & Cronin, 2008). Vertical stiffness refers to the relationship between maximum force, and vertical displacement of the centre of mass (Brughelli & Cronin, 2008). It has been shown that in running applications, increases in running velocity are met with increases in vertical stiffness, and increases in knee joint stiffness. Ankle joint stiffness however is unaffected by running speed (Brughelli & Cronin, 2008). This result was supported by Kubo et al. in 2007 who looked at ankle stiffness and tendon stiffness on jump height performance, they found that there was no correlation between jump height and ankle joint stiffness. However, the study did show that tendon stiffness was a contributing factor to increase jump height during countermovement jumps over squat jump performance. It has been shown that in hopping tasks, leg and ankle joint stiffness increase in conjunction with the decrease in ground contact time (Arampatzis, Schade, Walsh, & Brüggemann, 2001). This study further concluded that Leg stiffness influences vertical takeoff velocity and mean mechanical joint power in hopping tasks.

Given that the body alters the stiffness of the legs in accordance to different tasks being performed (Arampatzis et al., 2001; Brughelli & Cronin, 2008; Butler, Crowell, & Davis, 2003; Kubo et al., 2007), several studies have examined means of specifically altering joint stiffness properties (Wannop et al., 2015). In the study by Wannop et al. in 2016, elastic elements of different stiffness were fixed to a pair of shorts to increase passive joint stiffness by up to 5% during a vertical jumping task. Jump height improvements were achieved by subjects under different stiffness conditions. It was speculated that the increased hip joint stiffness in turn decreased the hip’s angular velocity during the squat jump, that in turn shifted the muscles towards an optimal force-velocity-power convergence (Wannop et al., 2015).

Exoskeletons

To improve human performance, various mechanical apparatuses to assist the body’s musculoskeletal system have been proposed since as far back as the early 1800’s (Wietse Van Dijk, 2015). Human exoskeletons can be classified into two categories: Active exoskeletons, that use motors to actively add energy to the system, and Passive exoskeletons that rely on the properties of elastic energy storage and return to augment task performance (Wietse Van Dijk, 2015). The benefit of passive systems is that they offer less added weight to the user. Passive exoskeletons may be sub-classified into hard exoskeletons, typically using composite springs built into a mechanism, which surrounds a limb; and soft exoskeletons, utilizing soft elastic elements in conjunction with more mobile clothing.

Passive elastic exoskeletons have been designed for hopping (Farris et al., 2013) and running applications (Cherry, Kota, & Ferris, 2010; Elliott et al., 2013a). Some intriguing interactions have been revealed. For instance, Grabowski and Herr (2009) found that subjects wearing an exoskeleton consisting of leaf springs parallel with the legs adjusted their leg stiffness so that the combined stiffness of the leg and spring system was roughly equivalent to the stiffness seen in the legs without the exoskeleton. This shared work between the human and mechanical systems meant that the body used 12-19% less energy depending on the configuration of the springs while hopping with the exoskeleton. In another study by Farris et al. (2013) a passive exoskeleton around the ankle joint was developed to assist in hopping tasks. They found that while hopping with the exoskeleton, metabolic cost was reduced, as was the maximum ground reaction force; however, the average mechanical power remained constant to when hopping without the exoskeleton. The findings of these studies show that when performing an athletic task, an exoskeleton can be utilized to decrease energy expenditure by the person wearing it, thus potentially increasing their endurance for the given task.

In a more dynamic motion like running, the interaction between used and exoskeleton become more complex. Due to the swing phase in running where the leg must be repositioned, elastic elements must disengage in order to allow free leg swing, then re-engage at heel contact to store elastic energy. Elliott et al. in 2013 solved this problem by incorporating a mechanical clutch to engage and disengage the carbon fibre spring elements at specific time points relative to the gait cycle in running. While the study successfully solved the problem associated with repositioning in gait, the exoskeleton was uncomfortable to wear and heavy (over 700g for each leg). This study underlines the importance of addressing the human-exoskeleton interactions. While sports equipment may be well engineered, if its interaction with the human body is not accounted for, performance may not be enhanced as predicted and in some cases can even suffer (Stefanyshyn and Wannop in 2015). While these systems all rely on complex orientations of elastic elements and mechanical structures, simpler designs have shown promise as well.

The design of exoskeletons using “exotendons” to store energy is a relatively new branch of study (Graves, 2013; van den Bogert, 2003; W Van Dijk, van der Kooij, & Hekman, 2011b; Wietse Van Dijk, 2015). These offer relatively lower weight and increased mobility for the user than compared to active exoskeletons. For instance, Van Dijk et al. in 2011 tested a 6kg exotendon system allowing 6 degrees of freedom for each leg in a walking application. Still, metabolic cost were 6% higher than walking without the system (W Van Dijk et al., 2011a). Yet lighter and more subject familiarization time with the exotendon systems may have shown improvements to their performance rather than deficits (Elliott et al., 2013b; W Van Dijk et al., 2011b). An alternate approach may be to focus on joint stabilization (Elliott et al., 2013a; Grabowski & Herr, 2009) rather than energy storage (Herr, 2009).

In summary, it follows that in order to create an exoskeleton system which can truly improve skating performance, it should be light weight, and comfortable for a person to wear and skate in for a variety of skating tasks. It follows that incorporating such a design into the existing restrictions associated with modern hockey protective equipment could prove highly beneficial to skating performance.

RESEARCH ARTICLE

Introduction

Ice hockey is a traditionalist sport with a long history in Canada (Pearsall et al., 2000). Despite this long history, research involving the biomechanics of the sport is quite sparse. For years, most questions regarding the biomechanics of ice skating have focused on speed skating biomechanics. While these studies give insight to understanding locomotion on ice, the general movement patterns cannot be translated directly to ice hockey due to the differences in equipment as well as sport dynamic. Unlike speed skating, which involves the same motions repeated for extended periods of time, ice hockey is a multiplayer, tactically dynamic sport in which individual skaters are required to start, stop and change direction many times per minute.

Technology in sport has grown to play a major role in the performance of elite athletes in recent years. In hockey, this has been seen in the improvement of skates and hockey sticks with improved material and fabrication engineering. Equipment made of wood and leather equipment has now been replaced by carbon fibre and composite materials. These developments have offered players with more robust equipment, retaining their material properties and consistent feel. Most of the apparel and personal protective equipment worn in a game has seen similar adoption of synthetic materials primarily developed to protect the player from impacts. However, design changes to enhance ice hockey skating performance have not been explored.

It follows that a natural advancement of technological equipment in ice hockey to improve skating performance is on the horizon. This study is the first of its kind, to implement a system of storing and returning energy to an athlete within the skating stride on ice. The purpose of this study was to examine how skating acceleration performance could be augmented through the use of soft, passive exoskeleton elastics to store and return elastic energy at the hip. It was hypothesized that participants would see improvements to their skating performance while utilizing the system of elastic elements, and that these improvements would be attributable to changes in the kinematics of the hip joint. Based on previous research however (Wannop et al., 2015), it was also hypothesized that individual participants would achieve their optimal performance under different elastic stiffness conditions.

Methods

Participants

Nine elite male hockey players took part in the study. Elite skill level was defined by the participants playing at a minimum level of Canadian USports League, with many participants playing at higher levels. All participants fell between the ages of 21-33 years and were free of lower body injury at the time of testing. The number of nine participants was chosen as previous studies have shown samples similar in size to this to provide sufficient statistical power (Renaud et al., 2017; Shell, 2016).

Table 1. Subject demographics

Age (years)	Height (m)	Weight (kg)	Leg Length (m)	Experience (years)	Skate Size
24.11 (3.54)	1.80 (0.07)	85.4 (7.97)	0.94 (0.04)	19.8 (3.42)	8 (1.37)

Instrumentation

Vertical jump tests and anthropometric measures were collected in order to establish measures which would be used to analyze the data. To measure jump height, a force plate (Type 9260AA, Kistler AG, Winterthur, Switzerland) sampling at 1000Hz was used and the methodology introduced by Ditroilo et al. in 2011 was employed to calculate jump height and peak power. Contact with the force plate was established as any force value exceeding 10N, and take off and touch down time points were based on crossing this threshold. The force plate was also used to measure the mass of each subject. Small bone calipers (model 01294, Lafayette Instrument Company, Lafayette, Indiana, U.S.A.) and a tape measure were used to take anthropometric measurements of the subjects, including: leg length and measurements of knee, ankle and shoulder joint widths which would be used in the computation of a computer model.

On ice testing was conducted using an 18 camera VICON motion capture system (Vicon©, Oxford, UK) sampling at 240Hz to measure kinematic and time component variables such as task completion time. The system consisted of 4 Vantage V5 cameras, 4 Vero cameras, 2 T40S cameras, and 8 T10S cameras. The motion capture equipment was calibrated prior to each testing session and captured a volume which was 15m long, 3m wide and 2m tall as seen in figure 1 below.

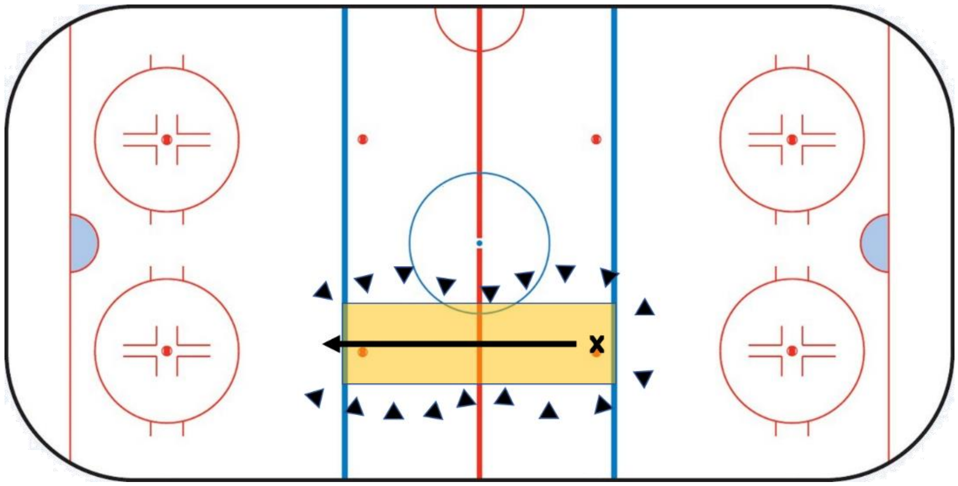

Figure 1. A representation of the on-ice testing set up, where motion capture cameras are represented by black triangles and an approximation of the calibrated capture area appears highlighted in yellow. “X” shows the starting position for each acceleration trial, and the arrow represents the skating trajectory of each participant.

Kinetic data during the one ice portion of the protocol was collected by using a custom-built load cell arrangement which was fitted to the skates. This instrument consisted of a 500kg load cell (Panther 247AS-500kg) wired to a transmitter node (SG-Link RGD-LXRS, Lord Microstrain, Williston Vermont, U.S.A.) which collected data at 256Hz. The load cell data was collected using Lord SensorConnect version 8.8.15, and data was exported after each trial as a .csv file. One load cell was mounted to each skate using a 3D-printed bracket which could be quickly changed between skate models and sizes. This load cell measured the deflection between the skate blade holder, and boot of the hockey skate, which through calibration on a force plate (Type 9260AA, Kistler AG, Winterthur, Switzerland) gave a proxy measure of force being transmitted through the skate to the ice normal to the skate blade.

Elastic Assistance System Design

Development of the exoskeleton used in testing was guided through a Pugh matrix (Appendix D). This matrix showed that a soft exoskeleton would be more appropriate than a hard exoskeleton due to the relatively low cost, ease of adjustment and individuality associated with that type of system. The hip joint was chosen as the joint of focus as it is the primary force contributor to the skating stride, and could be incorporated in an area where participants are already accustomed to wearing restricting equipment. It was decided that the elastics would be secured to the participants using a system of straps rather than modifying pre-existing hockey equipment, as this reduced the potential of slippage, and increased the adjustability for each participant.

Early on in preparation for this study, numerous design choices were made regarding the construction of the system of elastic assistance which would be used in the testing. When deciding which joints the elastic elements should span, the entire lower extremities were considered. As the hip is the prime joint associated with skating power, it was selected as the area of focus for this system. The choice to use latex elastic bands came from their low associated cost, low weight, as well as high degree of adjustability. These attributes made them the clear choice when compared to rigid composite springs used in some other systems as shown through the Pugh matrix attached in appendix D. The system was also designed to be as light weight as possible. This meant minimizing the hardware required for the attachment of the latex elastics. A modified climbing harness (Momentum Harness, Black Diamond, U.S.A.), with aluminum cam buckles attached to the leg and hip bands was used. These cam buckles provided a secure hold on the latex elastics ensuring that no slipping occurred, while also keeping the weight down. When fully assembled (figure 2), the entire system including latex elastics had a mass of only 850g. Velcro straps were sewn to the inside of the leg bands in order to ensure their placement on the legs did not change throughout testing. Through a full hip flexion range of motion, the system allowed for a change in length of the elastic elements of between 11 and 23cm depending on the size of the individual wearing it. Three different conditions of latex resistance elastics (Power Guidance Fitness Training, Suzhou, China) were selected for testing. Material properties of the latex were determined by measuring their change in length in response to added force in the method used by Triana and Fajardo (2012). The latex bands were hung from an aluminum cam buckle and weights were added to the free hanging end via a second aluminum cam buckle. Masses were increased in increments of 1kg until the length change in the elastic was greater than that seen in peak hip flexion. Five measurements were collected for each mass added.

Figure 2. A posterior view of a participant wearing the system of elastic assistance with the "Stiff" Elastic condition

Skate Force Measurement Apparatus

For the on-ice kinetic skate measures in this study, a wireless load cell attachment casing to fit between the bottom of the skate boot and top of the skate blade holder was constructed. These were easily transferable between skates of different sizes, and able to measure force measurements normal to the skate blade, at a point of application just posterior to the forward post of the skate blade holder. The electronics involved in the system included two 500kg load cell (Panther 247AS-500kg) connected to wireless transmitter nodes (SG-Link RGD-LXRS, Lord Microstrain, Williston Vermont, U.S.A.). The load cells were mounted to the blade holder of the skates using a custom 3D-printed mount. These mounts were size specific to each skate size used in testing, to ensure that measurements were consistent between trials and between skate sizes. Once mounted, the system added only 230g to each leg, the majority of this coming from the transmitter node which was secured to the shank with Velcro. The assembled load cell arrangement can be seen mounted to a skate in figure 3.

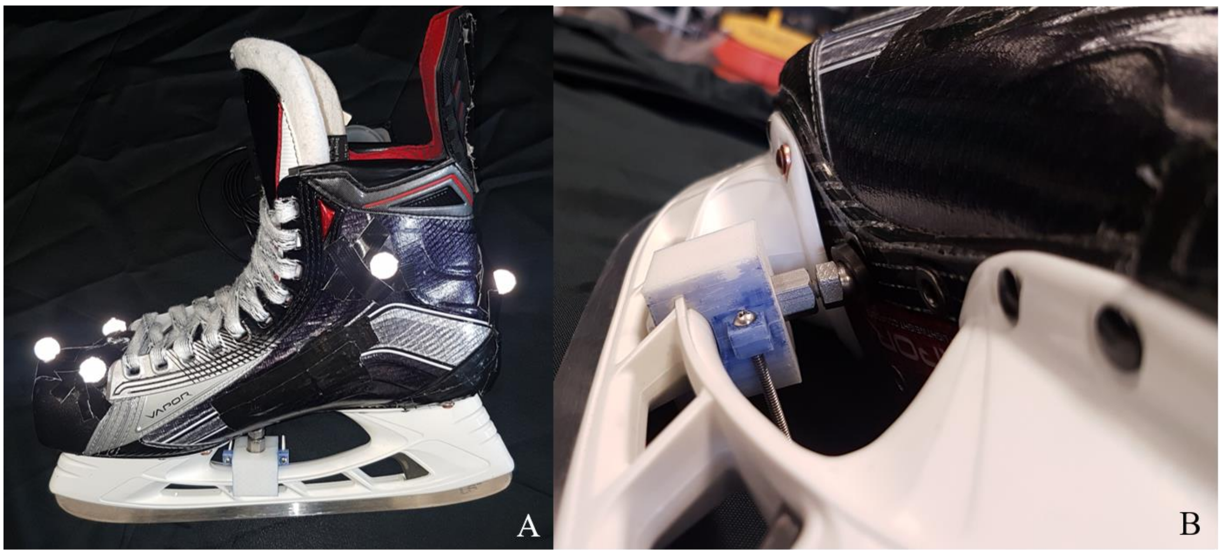

Figure 3. A) A skate instrumented with the force sensor and with reflective markers, B) displaying how load cells were mounted to the skate blade holder.

Load cell calibration was performed in a manner similar to that by (Stidwill, Turcotte, Dixon, & Pearsall, 2010). With the skate secured to a foot form and placed atop a force plate (Type 9260AA, Kistler AG, Winterthur, Switzerland), force was applied through a lever as shown in figure 4. Concurrent measures of force were taken through the load cell arrangement as well as the force plate, and the traces of each trial aligned. These concurrent measures were then fit using a third order polynomial fit in order to gain a calibration equation to convert the mV outputted from the load cell to Newtons. Calibration fits were performed for three trials of every skate size used in testing and average values were taken to generate the calibration equation. At the time of collecting this data, trials were also collected while altering the point of application of the force on the skate blade, this enabled researchers to gauge the sensitivity of the measurements obtained.

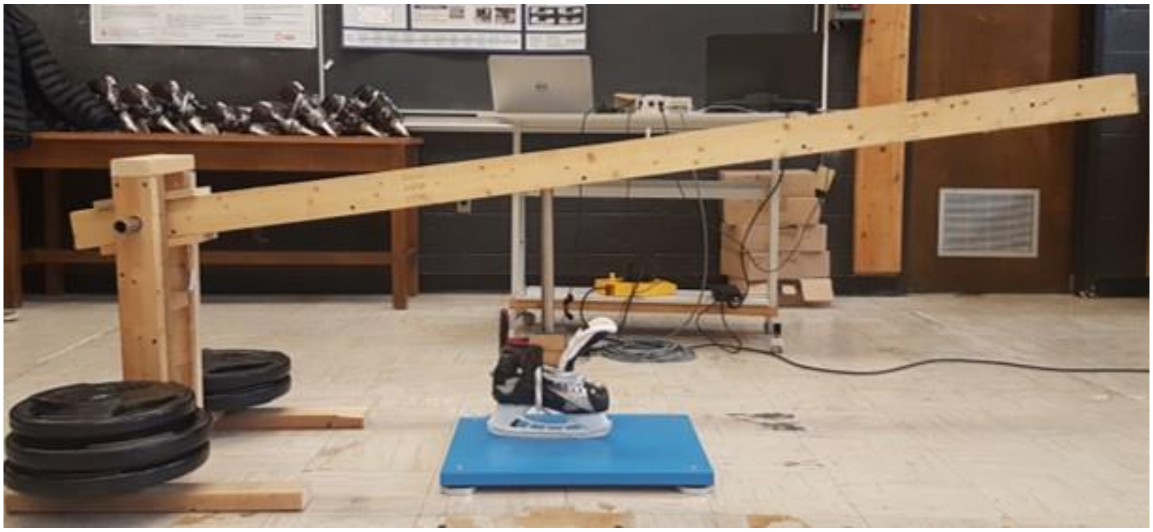

Figure 4. The load cell calibration apparatus

Experimental Protocol

Upon arrival, study participants were briefed on the testing protocol and signed a consent form which followed the guidelines of the McGill human Research Ethics Board II. Following the briefing about what participation entailed, participants were instructed to change into a provided suit (OptiTrack Motion Capture Suit, NaturalPoint Inc. Corvallis OR, United States) which was tight fitting, and covered in Velcro in order to allow the attachment of retroreflective markers. Data collection began prior to the participants taking to the ice with several off-ice measurements. Anthropometric measures were taken including height, weight, leg length as well as ankle, knee and shoulder width measures used to build a computer model using the kinematic data. Following the anthropometric measures, participants donned the system of elastic assistance, and moved to the force plate to perform maximal vertical jumps. Each participant performed 2 squat jumps under each of the three elastic conditions and a fourth control condition. The order in which they performed these trials was randomized prior to testing. Vertical jump height data was collected using a force plate (Type 9260AA, Kistler AG, Winterthur, Switzerland) sampling at 1000Hz and the jumps were filmed in the sagittal plane using a digital camera (Hero3+ Silver Edition, GoPro Inc., U.S.A.) to track the motion of the hip joint to establish a measure of leg stiffness. Following these procedures, the participant had 48

14mm spherical retroreflective markers applied to anatomical landmarks in accordance with a modified VICON Plug-in Gait marker set, using the Collins pelvis model (T. D. Collins, Ghoussayni, Ewins, & Kent, 2009) seen in figure 5.

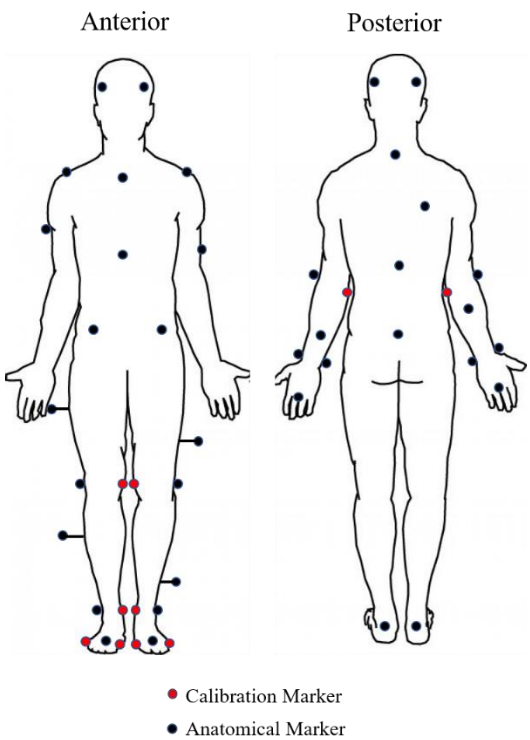

Figure 5. Representation of placements for 48 spherical retroreflective markers.

The participant then put on the provided skates (Bauer Hockey Ltd. Vapor 1X model) which had been fitted with the load cell arrangement. Skate sizes were available to match the participant’s preference. Immediately following this, participants skated out to the middle of the capture area to collect static calibration trials, still wearing the system of elastic assistance. Static calibration ensured that all markers would be visible to the cameras during testing. Calibration trials consisted of a static T-pose, as well as a bent elbow static pose which were both captured in the Nexus software for 5 seconds. Following these, subjects performed and two dynamic calibration trials consisting of left and right hip flexion, extension and abduction to establish functional hip joint centres. These trials served as a reference during data processing and the base measurement for the calculation of relative joint angles. Calibration markers were removed from the participant’s suit.

The participant was then permitted to skate freely and warm up. Subjects were given 5 minutes to skate freely around the rink to familiarize themselves with the skates they were wearing, as well as the feeling of skating while wearing the harness which held the elastic elements. Once the participants were comfortable and ready to skate the first elastic condition was mounted to the harness. The order of elastic conditions for each subject was the same order in which they performed their vertical jumps. The participant then performed a skating acceleration task from a forward facing stopped position through the 15m long capture area. Participants were instructed to begin each trial with a small vertical jump before accelerating through the capture area (to synchronize kinetic and kinematic measures), and were free to begin skating with whichever foot they preferred to lead with. Three trials for each elastic condition were completed, as well as three trials with no elastic elements in place. Between each trial, the system of elastic elements was visually inspected to ensure their position remains consistent between trials, and participants were given a one-minute rest interval between trials to reduce any fatiguing effects. Following each of the sets of three accelerations, the subject was allowed a 5 minute period of rest. During this rest period, the elastic elements were switched out, and the participant completed a Visual Analog Scale questionnaire (Appendix C) about their opinions of the system.

Condition Groups

Four test condition groups were created consisting of each participant's data under each of the three different elastic and one control condition with no elastic assistance. A fifth condition group titled "Best Elastic" was a composite of each participant's best skating performance while wearing one of the three elastic conditions. Planned comparisons were between the control condition and each of the four elastic condition groups. This allowed us to not only measure the overall effects of differing amounts of elastic assistance, but also the effects of a system personalized to the individual athlete.

Data Analysis

Video data collected during the vertical jump tests was imported into Dartfish software (Dartfish TeamPro Data 7.0, Fribourg, Switzerland) where the greater trochanter marker was tracked. Measurements were taken to determine the vertical displacement of this marker during the landing of each jump. Force plate data was processed in MatLab (Mathworks, Natick, Massachusetts, U.S.A.). This custom script calculated the impulse generated during the takeoff of the jump and used this to calculate vertical jump height (Moir, 2008). The custom script also output peak landing force, which was used in conjunction with the vertical displacement of the greater trochanter to gain a proxy measure of vertical leg stiffness.

Kinematic data was processed using VICON Nexus 2.2.5 software where trials were digitized based on two or three cameras being required to create a trajectory, dependent on data quality. Each trial was fully gap filled in the Nexus software using pattern and rigid-body fills. For small gaps in the data Woltring filling was used, automatically filling any gaps which were had fewer than 12 frames of data missing. Once every trial was gap filled, participants' trials were run individually through a custom Visual3D (Ver 5.01.23, C-Motion, Germantown, Maryland, United States) pipeline. In this pipeline the kinematic data was filtered using a 4th order low pass Butterworth filter with a cut off frequency of 8Hz. The pipeline added events corresponding to skate "ON" and "OFF" events according to Hreljac and Marshall (2000), where ON events were determined as a peak in heel marker vertical acceleration. Skate "OFF" events were determined by the Jerk of the toe marker crossing zero in the anterior/posterior direction. Following the pipeline, each trial was visually inspected and adjusted to insure the accuracy of these events. During this visual inspection, two additional events were added corresponding to the landing of the initial jump at the start of each trial. These events were identified by the peak in toe marker vertical acceleration. Once all nine participants had been run through the Visual3D processing, the data was brought into MatLab (Mathworks, Natick, Massachusetts, U.S.A.) for analysis using a custom script based on the Biomech Zoo toolbox (Dixon, Loh, Michaud-Paquette, & Pearsall, 2017).

After the kinematic data had been processed and converted to the .zoo format, the raw kinetic data was added to each file. Initially, the kinetic data was filtered using a zero-offset 4th order low pass Butterworth filter with a cut off frequency of 16Hz. Following filtering any missing values which had been dropped during collection were interpolated using a shape-preserving piecewise interpolation function. Following this, the data was down-sampled from 256Hz to 240Hz so that it could be synced with the kinematic data. Peaks in the kinetic data were identified, and the second peak was then set to the same sample number as the jump landing event in the kinematic data which was defined previously in Visual3D. This was visually inspected for every trial to ensure that kinetic and kinematic trials were aligned correctly, and modifications were made in the cases where the second peak in kinetic data did not represent the jump landing. Once the two data sets were aligned they were cut to the same length. This step was required as the kinetic data always collected for 15 seconds, whereas the kinematic trial length varied by trial.

Once the two data sets had been aligned and concatenated in a single .zoo file, processing resumed. A representative trial was selected for each condition under each participant according to Dixon, Stebbins, Theologis, and Zavatsky (2013). This representative trial was derived from kinematic variables of the hip, knee, pelvis, and trunk, spatiotemporal variables regarding center of mass acceleration and position as well as the force collected for each skate. Representative trials are chosen based on an analysis of root mean squared error between each curve, and the mean of all curves for the specified variables. The trial which had the smallest difference to the mean across the specified variables was selected as the representative trial. This method was chosen as it allows for the analysis of a collected trial, rather than the averages of several trials. These representative trials were used in the analysis of all kinetic, kinematic, and spatiotemporal variables regarding the skating task.

As the starting limb for each trial was not controlled for, left and right limbs were renamed to “Side1” and “Side2”, where the “Side1” limb was the leg used for the first step. This allowed for the comparison of like movements regardless of participant leg dominance. After this transformation, each trial underwent a coordinate system rotation. As the capture area was quite wide, some participants could skate at a slight diagonal to the established lab coordinate system defined during calibration. To correct for this, the center of gravity trajectory was analyzed and the direction of forward progression was set as the new positive-y direction. This step ensured that the values for time to skate 9m were accurate to the direction of progression of the participant, and any deviation away from the lab coordinate system would not be considered.

Statistical Analysis

Statistical tests were performed using SPSS Statistics (IBM Corporations, Somers, U.S.A., Version 24). Time to skate 9m analysis was performed using a paired samples t-test to compare each elastic condition to the control condition. Means and standard deviations were calculated for all kinetic and kinematic variables for each of the conditions tested. Comparisons were made between each elastic condition and the control condition using planned comparison one-way ANOVAs for all kinematic, vertical jump and VAS data. Significance levels for each of the planned comparisons was set at $\alpha=0.05$, allowing for a familywise error rate of 0.185 (Keppel & Wickens, 2004).

Results

Characteristics and material properties of the elastic elements used in the exoskeleton system can be found in Table 2.

Table 2. Material properties of Elastic Elements

Elastic Condition	Cross Sectional Area (cm^2)	Average Stiffness (N/m) (±SD)
Soft	0.36	132.2 (20.8)
Medium	0.99	256.7 (38.1)
Stiff	1.53	440.8 (51.9)

As hypothesized, participants achieved their peak skating acceleration under different elastic conditions. The results in this section are displayed in rank order according to each of the four conditions tested ("Control", "Soft", "Medium", and "Stiff") as well as a fifth "Best Elastic" condition. Table 3 shows a breakdown of each condition including the average time to skate nine meters of all subjects, as well as how many participants achieved their best and worst performance under each condition.

Table 3. Skating Performance and Group Characteristics

Condition	Time to Skate 9 Meters (s) (±SD)	Best Condition	Worst Condition
Control	1.91 (0.01)	2	4
Soft	1.90 (0.08)	2	3
Medium	1.88 (0.08)	4	0
Stiff	1.92 (0.10)	1	2
Best Elastic	1.88 (0.08)	-	-

Off ice vertical jump tests were conducted to examine the effects of the elastic system on jump height as well as leg vertical stiffness. None of the elastic conditions tested provided any statistically significant benefit to jump height ($p>0.05$), nor did they have a measurable effect on leg stiffness as seen in Table 4. Jump height was not correlated to skating performance times in this study ($r=-0.016$, $p=0.925$).

Table 4. Off-Ice Test Performance

Condition	Jump Height (cm)	Leg Vertical Stiffness (kN/m) (±SD)
Control	29.1 (5.0)	15.6 (8.1)
Soft	27.9 (5.6)	19.7 (14.3)
Medium	29.1 (6.1)	15.3 (6.6)
Stiff	27.6 (6.2)	21.0 (13.2)
Best Elastic	28.8 (5.2)	19.5 (13.8)

Despite minimal differences between elastic bands in in the vertical jump results, greater differences in skating performance under different elastic bands were seen, though not at a level of significance. For skate time, the "Medium" stiffness condition showed an average improvement of 1.2% (p=0.065), and the "Best Elastic" condition showed an average improvement of 1.5% (p=0.052) when compared to the control condition (Figure 6). However, skaters' responses were not systematic between elastic bands. Maximum velocity achieved after each subject's 6th step was consistent between band conditions though the corresponding distance traveled was 20cm shorter in the "Best Elastic" condition (Table 5, p=0.726) this condition also showed the highest average cadence (p=0.475).

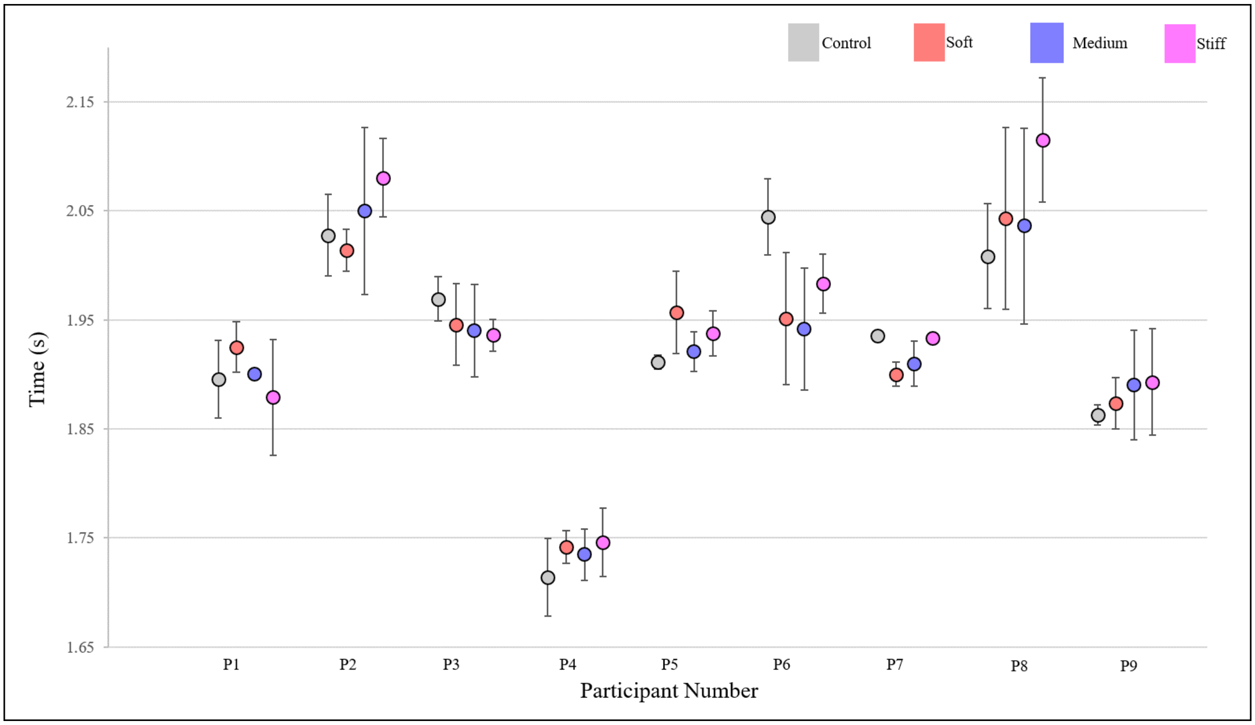

Figure 6. Time (±SD bars) to skate nine meters for each of the nine participants in each of the four test conditions.
*Lower number represents a faster skating time

Table 5. On-Ice Spatiotemporal Variables Related to Skating Performance (mean ± SD)

Condition	Time to skate 9m (s)	Velocity after 6 steps (m/s)	Distance after 6 steps (m)	Cadence (Steps/s)
Control	1.91 (0.10)	6.54 (0.236)	7.63 (1.09)	3.56 (0.48)
Soft	1.90 (0.08)	6.48 (0.270)	7.62 (0.99)	3.60 (0.55)
Medium	1.88 (0.08)	6.59 (0.259)	7.66 (0.87)	3.66 (0.44)
Stiff	1.92 (0.10)	6.49 (0.268)	7.63 (0.95)	3.52 (0.42)
Best Elastic	1.88 (0.08)	6.57 (0.268)	7.46 (1.01)	3.69 (0.48)

Step length was determined by the distance the toe marker traveled in the direction of progression from one skate ON event to the subsequent opposite skate ON event. These distances were then normalized to each participant's average leg length (ASIS to the lateral malleolus). No significant differences were observed between any of the elastic conditions and the control condition ($p>0.05$) for any of the six steps (Table 6). However, the best elastic condition had shorter (~ 5.5 cm) average step lengths than the control in four of the six steps measured.

Table 6. Normalized Step Length (±SD) for the First Six Steps of Acceleration

Condition	Step Length as a Ratio to Leg Length					
	Step1	*Step2*	*Step3*	*Step4*	*Step5*	*Step6*
Control	1.04 (0.04)	1.19 (0.10)	1.46 (0.09)	1.70 (0.30)	1.99 (0.21)	2.10 (0.13)
Soft	1.06 (0.07)	1.19 (0.13)	1.45 (0.23)	1.60 (0.22)	1.94 (0.31)	2.17 (0.34)
Medium	1.10 (0.09)	1.20 (0.10)	1.44 (0.19)	1.64 (0.22)	2.00 (0.17)	2.19 (0.36)
Stiff	1.05 (0.09)	1.22 (0.09)	1.48 (0.16)	1.68 (0.27)	1.98 (0.21)	2.23 (0.28)
Best Elastic	1.08 (0.09)	1.17 (0.11)	1.41 (0.22)	1.64 (0.23)	1.90 (0.26)	2.18 (0.37)

The skating start's strides transition from running to gliding. As such, the amount of time both skates are in contact with the ice, knows as double support time, increases with each stride. While the amount of double support time changed between each stride, there were no significant differences in this measure introduced by the band system (Table 7).

Table 7. Double Support Time (±SD) for the First Six Steps

Condition	Double Support Time (s)					
	Step1	*Step2*	*Step3*	*Step4*	*Step5*	*Step6*
Control	-0.008 (0.05)	-0.032 (0.03)	0.001 (0.02)	0.026 (0.03)	0.035 (0.02)	0.036 (0.04)
Soft	0.003 (0.05)	-0.038 (0.05)	-0.003 (0.03)	0.007 (0.04)	0.026 (0.02)	0.042 (0.04)
Medium	0.004 (0.06)	-0.038 (0.04)	-0.010 (0.04)	0.011 (0.02)	0.029 (0.02)	0.043 (0.03)
Stiff	0.009 (0.06)	-0.027 (0.04)	-0.003 (0.04)	0.008 (0.04)	0.025 (0.03)	0.034 (0.02)
Best Elastic	0.016 (0.06)	-0.036 (0.04)	-0.004 (0.03)	0.008 (0.03)	0.024 (0.02)	0.031 (0.03)

*Negative values represent a “flight phase” where neither skate is in contact with the ice.

Skating kinematics were largely unaffected by the introduction of the elastic elements; however, the hip did show some small yet significant differences between conditions. In general, few differences in peak hip flexion and hip extension for elastic conditions versus the control were observed (Table 8, $p>0.05$). However, these differences were small (i.e. less than 5 degrees) in terms of the range of motion indicating that the hip kinematics were largely unperturbed by the elastic conditions (figure 7).

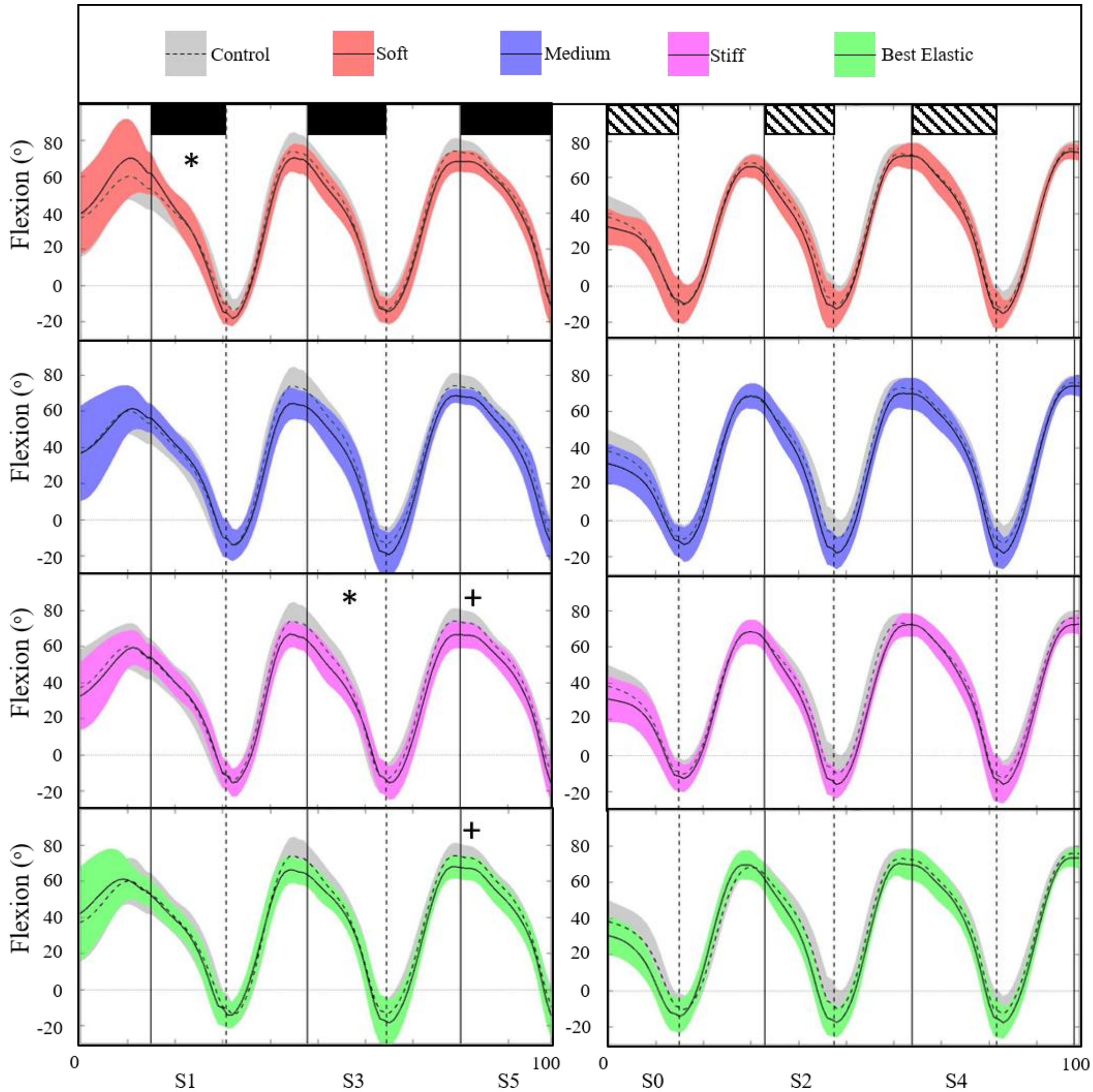

Figure 7. Hip Flexion (±SD shaded bands) during the First Six Steps.
Positive values represent flexion, and negative values represent extension.
* $p<0.05$ for the range of motion indicated in stance phase.
+ $p<0.05$ for the max flexion angle indicated in stance phase.
** The solid and dashed bars represent the stance phases of S1 and S2 legs, respectively. Data lines represent the ensemble averages of all participants, normalized to the length of six strides on the x-axis. Shaded regions represent one standard deviation of this data. Solid vertical lines represent a skate ON event, and dashed vertical lines represent a skate OFF event. Below the x-axis, stance phases are labeled with their number. S1-5 show the time between a skate ON event and the subsequent skate OFF event for the same leg. S0 represents the time from the start of the normalization (S1OFF) until S2OFF.

Hip Adduction was unperturbed by the introduction of elastic elements (figure 8). No elastic conditions were different compared to the control condition in terms of range of motion or maximal abduction during stance phases (p>0.05).

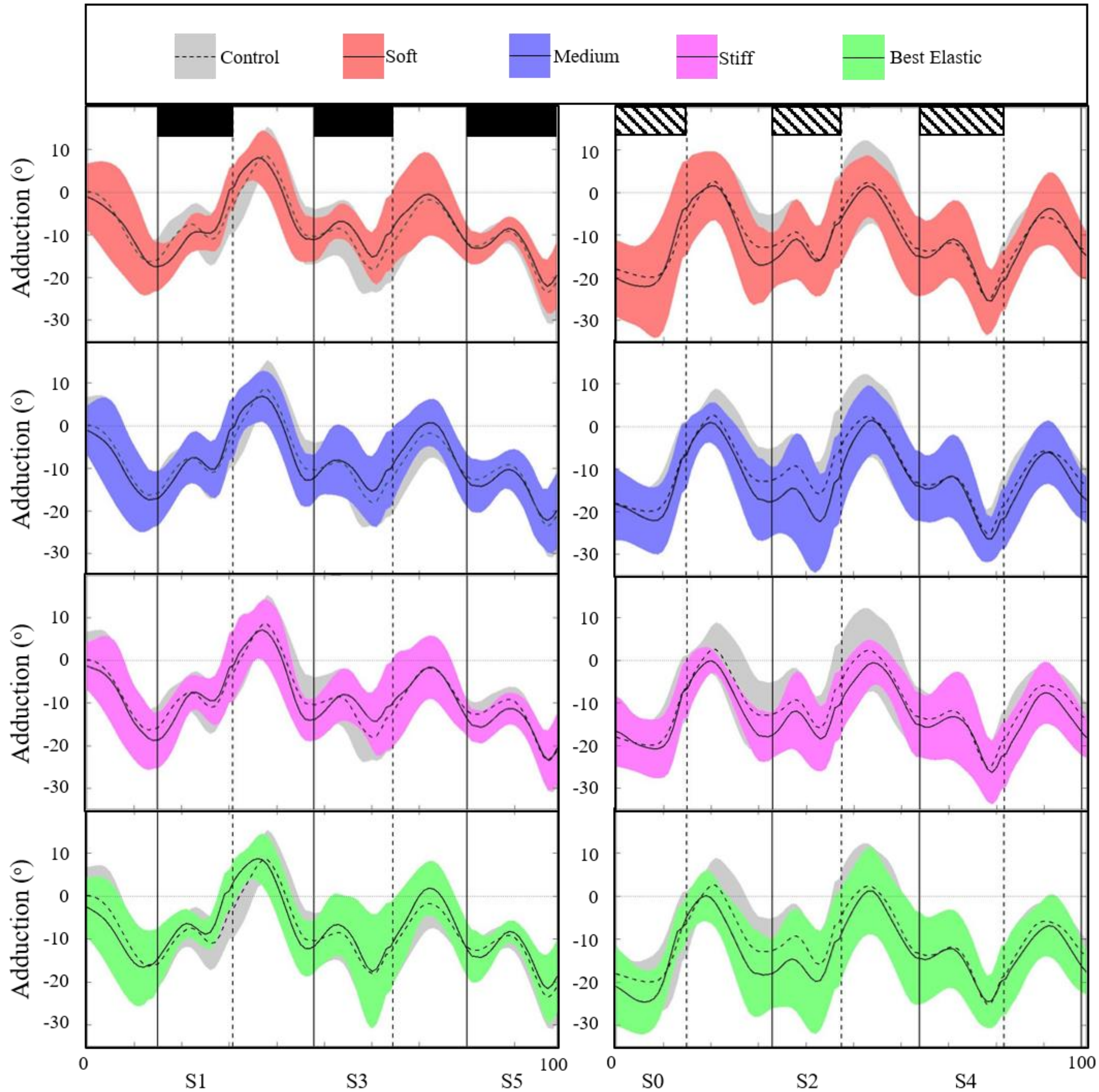

Figure 8. Hip Adduction for the First Six Steps.
**Adduction (+), Abduction (-)

Knee flexion kinematics were also unaffected by the elastic elements (Table 9, p>0.05). All elastic conditions showed a decrease in knee flexion variability compared to the control (Figure 9). In addition to this, the "Medium" and "Stiff" elastic elements tended to reduce knee extension cessation at ice contact (Figure 10). Though when normalized and averaged, these differences seen within individuals largely disappeared.

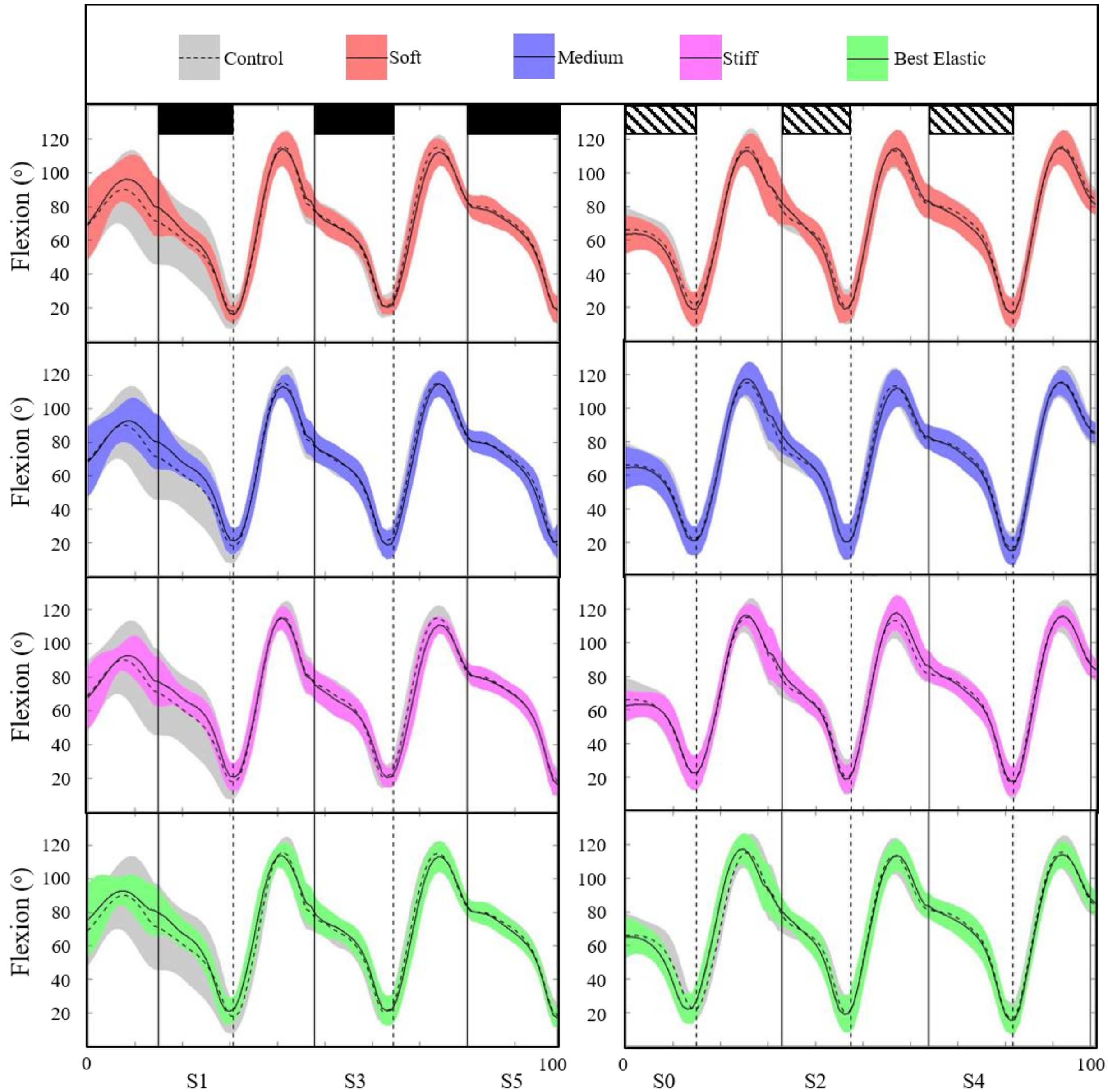

Figure 9. Comparisons in Knee Flexion over the First Six Steps between each Elastic Condition and the Control.

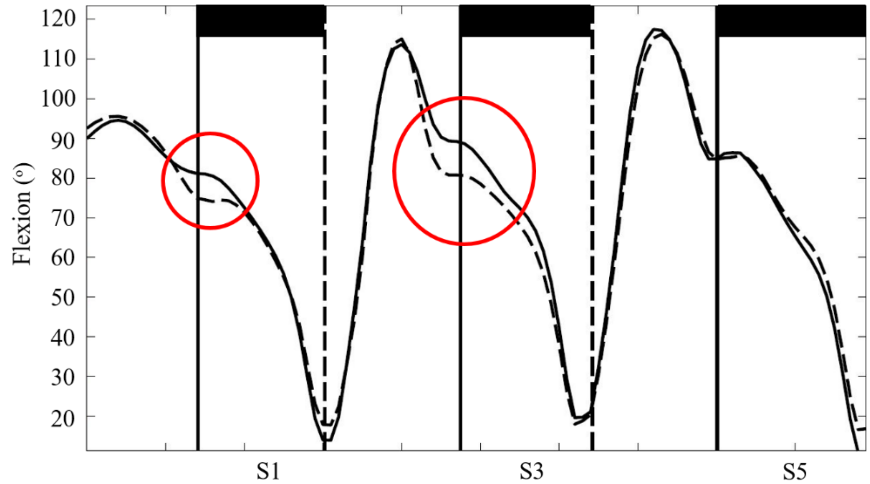

Figure 10. Knee Flexion of a Single Participant in the “Stiff” (solid) and Control (dashed) Conditions.

*Circled areas highlight the differences in knee extension occurring around initial ice contact.

Table 8. Hip Flexion Kinematic Measures over the First Six Stance Phases

Condition	Stance0		Stance1		Stance2		Stance3		Stance4		Stance5	
	Max (°)	Min (°)	Max (°)	Min (°)	Max (°)	Min (°)	Max (°)	Min (°)	Max (°)	Min (°)	Max (°)	Min (°)
Control	39.0 (11.8)	-9.0 (7.7)	50.7 (12.9)	-10.8 (8.4)	62.8 (6.7)	-6.9 (13.1)	71.8 (8.9)	-13.2 (8.9)	73.6 (5.8)	-11.2 (11.2)	74.1 (7.1)	-10.9 (10.0)
Soft	35.5 (8.9)	-7.7 (12.6)	**60.3 (16.8)**	**-15.6 (6.2)**	56.9 (13.7)	-10.7 (12.6)	65.7 (9.8)	-13.4 (6.9)	70.3 (8.1)	-13.0 (10.5)	68.8 (6.3)	-12.1 (11.2)
Medium	31.5 (11.0)	-11.4 (8.8)	56.4 (11.6)	-10.8 (10.6)	60.2 (14.7)	-15.6 (9.8)	61.2 (10.8)	-18.1 (12.0)	69.9 (9.1)	-15.9 (10.3)	68.7 (4.1)	-15.1 (11.6)
Stiff	32.2 (12.4)	-11.4 (8.3)	52.9 (10.7)	-11.6 (8.0)	61.6 (12.0)	-13.6 (8.7)	**61.3 (14.7)**	**-12.6 (9.4)**	70.7 (8.6)	-13.9 (12.2)	**67.2 (7.5)**	-16.51 (9.7)
Best Elastic	30.6 (10.6)	-12.6 (9.8)	57.3 (10.8)	-10.2 (9.9)	60.5 (15.1)	-16.1 (9.2)	62.9 (10.5)	-17.0 (13.2)	69.4 (9.3)	-15.7 (10.3)	**67.7 (7.1)**	-15.8 (12.0)

*__Bold__ Values indicate a Significant Difference ($p<0.05$) between an elastic condition and the control.

Table 9. Knee Flexion Kinematic Measures over the First Six Stance Phases

Condition	Stance0		Stance1		Stance2		Stance3		Stance4		Stance5	
	Max (°)	Min (°)	Max (°)	Min (°)	Max (°)	Min (°)	Max (°)	Min (°)	Max (°)	Min (°)	Max (°)	Min (°)
Control	68.7 (11.8)	21.2 (8.0)	66.3 (20.6)	16.6 (11.6)	74.9 (6.4)	19.6 (10.8)	77.6 (7.7)	17.2 (6.1)	83.5 (6.1)	16.0 (9.7)	84.4 (5.8)	16.8 (6.7)
Soft	65.0 (11.4)	17.6 (9.6)	74.5 (12.6)	15.7 (5.7)	74.5 (9.2)	17.2 (9.4)	75.5 (10.2)	18.7 (3.8)	80.8 (9.6)	15.4 (8.5)	81.1 (6.5)	17.0 (7.3)
Medium	66.6 (12.4)	19.5 (8.6)	74.6 (10.0)	20.5 (7.5)	77.1 (8.8)	18.6 (9.5)	77.2 (9.0)	17.6 (8.5)	83.6 (8.0)	13.9 (8.9)	83.2 (6.5)	15.8 (6.3)
Stiff	65.7 (8.7)	22.0 (10.1)	73.6 (8.4)	20.4 (8.1)	78.8 (8.5)	18.2 (8.1)	74.0 (12.0)	19.2 (5.5)	83.8 (6.7)	16.1 (8.4)	82.3 (6.4)	15.4 (6.8)
Best Elastic	66.0 (11.6)	21.0 (8.5)	77.8 (10.4)	20.6 (7.7)	76.8 (10.6)	16.2 (8.7)	77.3 (11.2)	19.5 (8.7)	83.4 (7.9)	14.1 (8.2)	82.3 (6.8)	16.0 (6.1)

The elastic conditions did effect the pelvis' kinematics. Anterior rotation range of motion was significantly reduced in the "Medium" (p=0.019), "Stiff" (p=0.029), and "Best Elastic" (p=0.051) conditions compared to the control condition during S2 (figure 11). This reduction also occurred during ST3 in the "Soft" condition (p=0.031), and again in the "Best Elastic" condition (p=0.091).

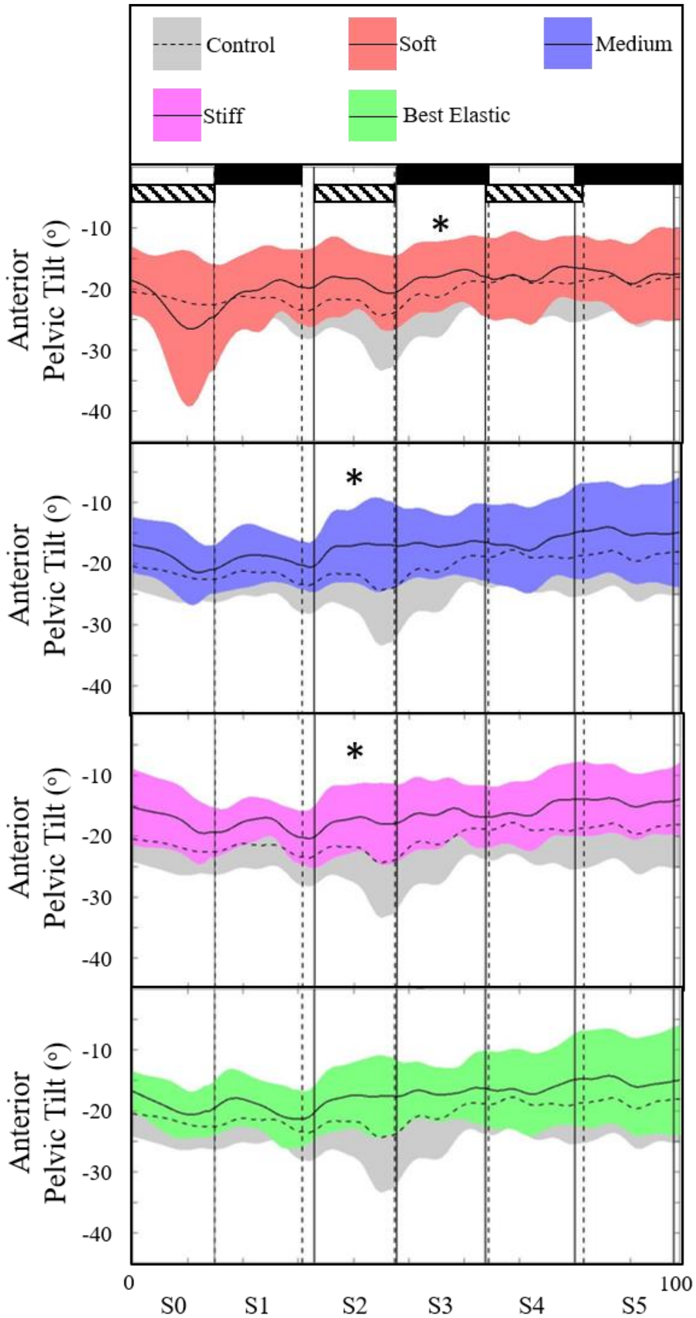

Figure 11. Anterior Pelvic Rotation during the First Six Steps.
* Represents a significant difference ($p<0.05$) for the range of motion in the indicated stance phase.
**Negative values indicate anterior pelvis tilt.

Lateral Pelvic rotation was not affected by the introduction of the elastic elements (figure 12), as no condition showed any significant difference when compared to the control condition (p>0.05).

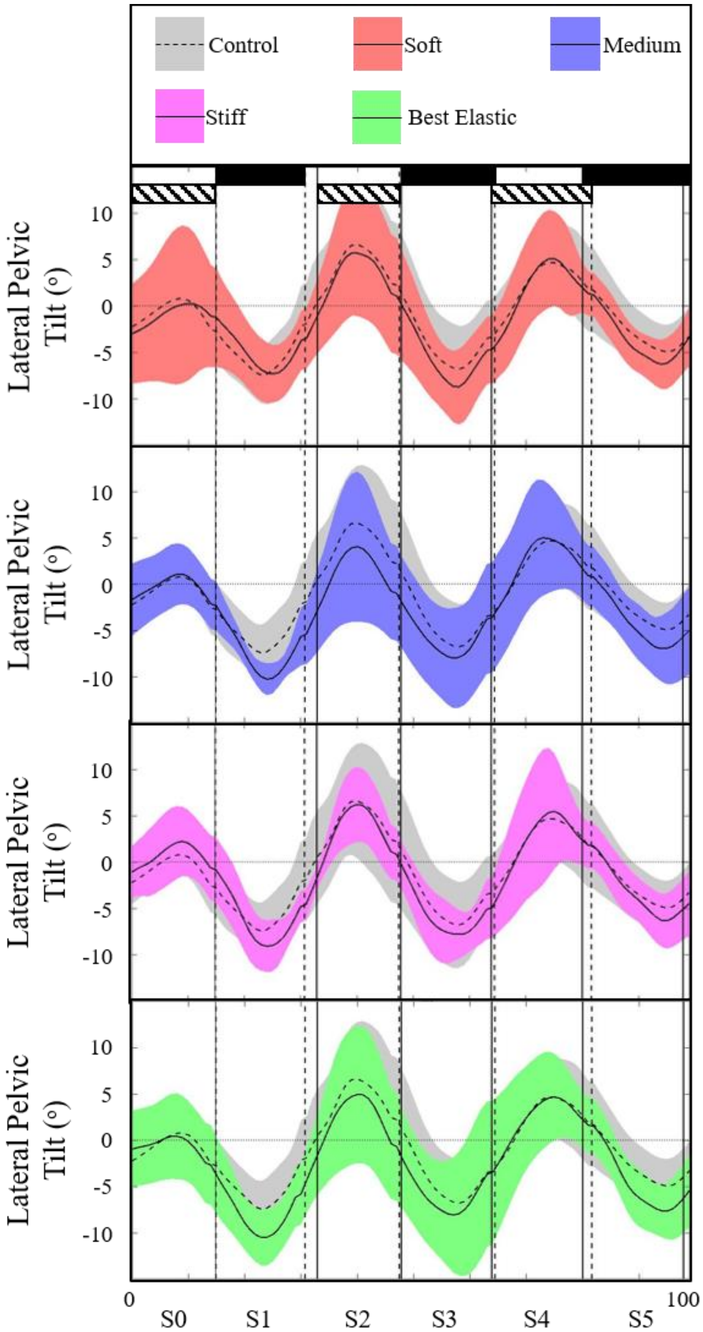

Figure 12. Lateral Rotation of the Pelvis During the First Six Steps.

The order in which subjects tested each elastic condition was randomized during testing. No condition order effects were detected (r=-0.222, p=0.193). Within conditions, trial number (trial 1, 2, 3 for each condition) showed a significant effect, with later trials being consistently faster than the first trial (r=-0.446, p<0.001) for elastic conditions but not in the control trials ((r=-0.251, p=0.226). This could potentially be attributed to a learning effect as participants became more familiar with each condition.

After the set of three trials under each elastic condition, participants completed a Visual Analog Scale (VAS) questionnaire regarding their perceptions of each condition with scores between 0 (none) to 10 (most) for each category on the questionnaire. A score of 5 would be regarded as feeling neutral toward the condition (Table 10, Figure 13). Few significant differences were found; though participants did note reduced mobility while wearing the “Stiff” elastic elements (p=0.029). Participants reported feelings of increased skating power and acceleration while wearing the “Medium” elastic elements, as well as when wearing their individual “Best Elastic” condition but these were not statistically significant (p>0.05).

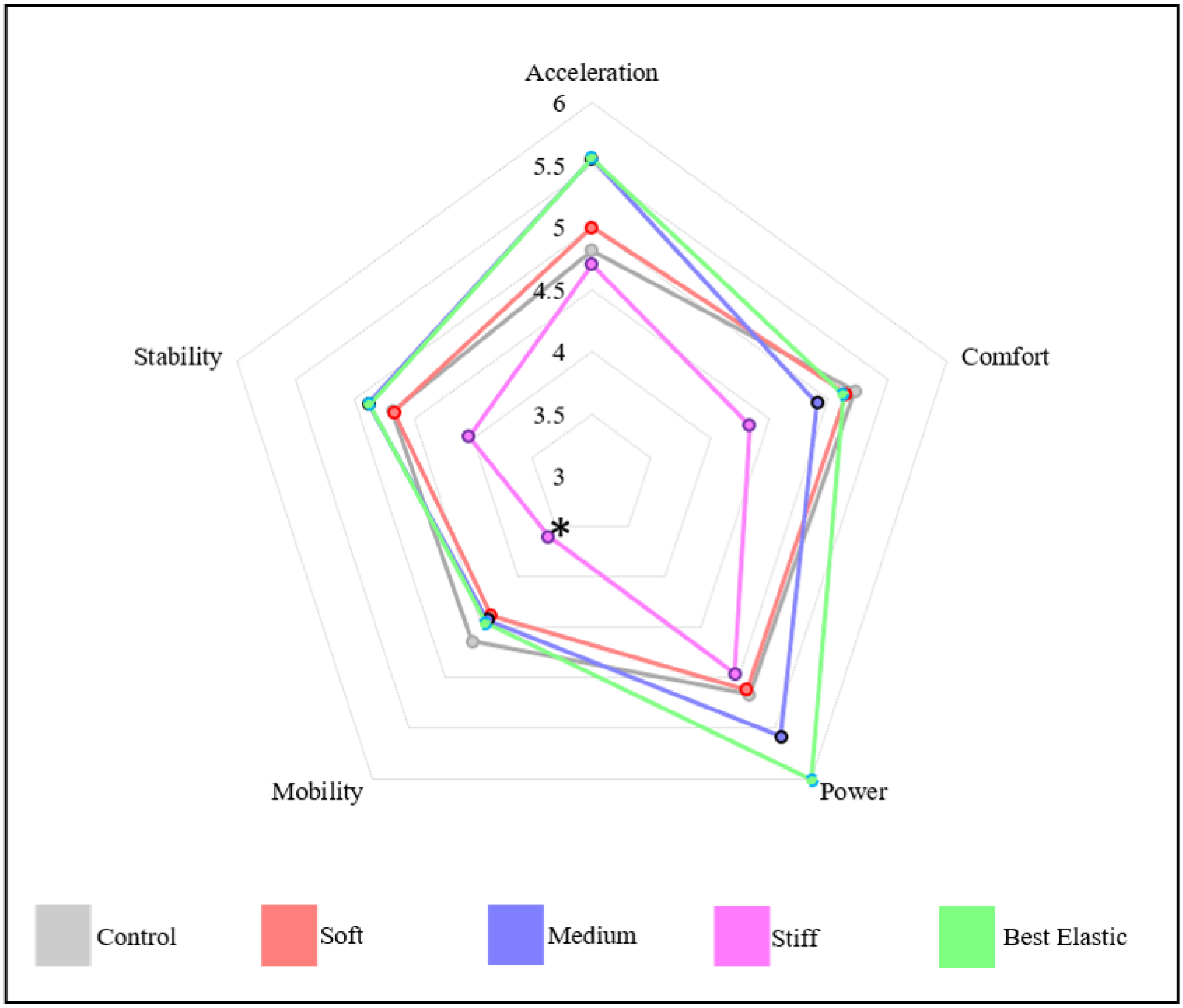

Figure 13. Participant Perceptions of each Elastic Condition.
* Represents a significant difference (p<0.05) compared to the control condition.

Table 10. Participant Perceptions of each testing condition

Condition	**Acceleration**	**Power**	**Mobility**	**Stability**	**Comfort**
Control	4.81 (0.61)	5.16 (0.64)	4.64 (0.44)	4.68 (0.41)	5.22 (0.82)
Soft	5.00 (1.27)	5.12 (0.98)	4.38 (0.69)	4.67 (0.59)	5.15 (1.02)
Medium	5.55 (1.70)	5.58 (1.54)	4.42 (1.06)	4.88 (1.07)	4.91 (1.35)
Stiff	4.70 (1.63)	4.96 (1.71)	**3.59 (1.59)**	4.04 (1.48)	4.33 (1.84)
Best Elastic	5.44 (1.40)	6.13 (1.32)	4.26 (0.69)	4.96 (0.98)	5.23 (1.40)

***Bold** indicates a Significant Difference (p<0.05) between an elastic condition and the control.

Kinetic (force) data was collected only for the left skate stances 0, 2, 4 (Table 11). There were no significant differences seen in maximal force measured during any of the stance phases between any elastic condition and the control. All force data reported was normalized to each participants body weight to remove any artifact caused by anthropometrics.

Table 11. Maximal Force During the First Six Stance Phases, Normalized to Body Weight

Condition	**Maximal Force Normalized to Body Weight**		
	Stance0	*Stance2*	*Stance4*
Control	0.876 (0.28)	0.704 (0.18)	0.761 (0.12)
Soft	0.943 (0.26)	0.734 (0.22)	0.843 (0.14)
Medium	0.885 (0.27)	0.663 (0.21)	0.763 (0.20)
Stiff	0.819 (0.34)	0.699 (0.14)	0.813 (0.13)
Best Elastic	0.926 (0.25)	0.720 (0.18)	0.785 (0.18)

Discussion

The exoskeleton configuration used in this study primarily focused on assisting the hip in the forward skating start, or more specifically, to providing extrinsic, increasing graded assistance to hips' muscles during eccentric flexion in early stance and subsequently assisting the hip muscles during concentric extension in push-off. The soft exoskeleton that consisted of a modified climbing harness with cam buckles to secure selected elastic bands in position posterior to the hip. This minimalist approach was light weight (850g) and conformed to each participant's individual anthropometrics.

Based on the differences in leg lengths and muscle mass posterior to the hip between participants, elastic elements had a maximum change in length of between 11 and 23cm. Given this distance, the "Soft", "Medium", and "Stiff" elastics provided maximal elastic assistance in the ranges of 14-30N, 28-59N, and 48-101N respectively. The VAS results demonstrated that participants were sensitive to changes in elastic stiffness and noted the corresponding resistance to hip mobility while skating. The latter perceived reduced hip mobility was interpreted negatively as it perturbed participants' sensation of hip flexion end points, and in turn their step to step stability.

VAS scores demonstrated participants perceived increased skating acceleration, in particular in the "Medium" and "Best Elastic" Conditions. For six of the nine participants, both of these conditions showed improved skating performance (shorter time) compared to the control condition. Elastic condition test order was randomized between participants. In addition, to minimize placebo effects, testers gave no feedback on individual trial times nor the relative stiffness of the elastic condition used. Participants' choice of preferred elastic resistance varied. This is consistent with W Van Dijk et al. (2011) study of exoskeleton systems, in that elastic elements had to be tuned to the individual preference to avoid undesired kinematic gait changes.

Unexpectedly, the elastic band assistance did not improve the vertical jumping task performance nor did it correlate with skating times. This is surprising, as previous studies have shown a positive correlation between vertical jump height and skating (Mascaro, Seaver, & Swanson, 1992). These differences may be attributed to the jump techniques imposed: in this previous study, a countermovement jump was examined where as in our study we tested jump height starting from a static flexed, squat position. The differences in plyometric versus non-plyometric techniques may explain the differing relation to skating found.

In this study, step lengths in the control condition were similar to those reported by (Shell, 2016). The elastic conditions did not affect the gross hip and knee kinematics nor skating push-off force; however, changes in spatiotemporal variables (i.e. decreased step length and increased cadence) were noted. Further, the elastic resistance did correspond to decreased pelvis anterior rotation that in turn may reduce the distal thigh forward rotation resulting in a shorter step length. It could explain why participants reported decreased perceived comfort as foot placement unexpectedly fell short and their anticipated point of balance on each stride was perturbed. As anterior pelvis rotation has shown to be beneficial to hip extension in running studies (Schache, Blanch, & Murphy, 2000), to compensate participants may have increased their cadence (and decreased double support time or flight time) to achieve similar accelerations per stride. These adaptations have been previously reported by Renaud et al. (2017) in high calibre skater's acceleration strides, and by de Koning et al. (1987) who found that higher skating speeds were achieved not by an increase in push-off force, but instead by a decrease in stride duration. Lastly, converse to the lower perceived comfort with foot placement, participants perceived the elastic conditions to provide more stability at push-off.

As the hip is the major power generator in the skating stride (de Boer et al., 1987; Jos J De Koning et al., 1991), the soft exoskeleton system was developed around the hip. The elastic elements ran posterior to the hip joint to store elastic energy during flexion and returned this energy during hip extension. However, the skating hip and knee range of kinematics were largely unperturbed (<5°) by the elastic assistance. Hip abduction kinematics also were not perturbed. This was expected based on the orientation of the elastic elements which followed the posterior thigh.

The knee displayed few changes in kinematics. Unexpectedly, for all elastic conditions tested, knee flexion variability as seen in the standard deviations during S1 (Figure 9, Table 9) was reduced by half. It is unclear if this reduction in variability is beneficial to performance and/or injury prevention. Another minor change in the knee kinematics was the reduction of the "Knee Extension Plateau" as discussed by Budarick (2017), referring to the phenomenon of a temporary cessation in knee extension following a skate contact with the ice. This knee extension plateau is exaggerated in female skaters, and is speculated in part to compensate for medial or varus knee drop behavior implicated in the increased prevalence of knee injury in female hockey players. For many of the participants this was reduced while they wore the "Medium" and "Stiff" elastic elements (Figure 10) however through averaging and normalization of the skating strides between individuals these differences disappeared from Figure 9. If true then altering the pelvis-hip movement with the elastic conditions may augment hip ergo knee stability, thus reducing the need to dampen knee extension. Although female participants were not included in this study, future studies should examine the effects of this system on knee extension in females, as reducing this plateau may decrease the prevalence of knee injuries.

While the differences observed in skating performance measures were few, this may be due in part to lack of familiarization with the elastic conditions. In the short period each subject had using the elastic system a significant trial-to-trial effect was observed, showing that for each successive skating trial in a given condition, skating performance improved. This potential learning effect was absent from the control condition. Umberger and Martin (2007) demonstrated that humans adapt their gait patterns over time in order to improve efficiency. Due to time constraints when testing, participants were only given a small amount of time to adapt to each new elastic condition. One may speculate that with an increase in familiarization time, the differences between elastic conditions and the control may have been larger than what was reported so far. This agrees with the findings of similar studies where performance seems to improve with increased time using a system of elastic assistance (W Van Dijk et al., 2011a). Similarly, Galle, Malcolm, Derave, and de Clercq (2013) were able to quantify this learning effect with an ankle exoskeleton where adaptation required at least 20 minutes of continued familiarization to fully achieve the benefits of their system.

This study has several limitations. These include: 1) time constraints associated with ice arena rentals and the set up and take down of testing instrumentation meant that participants were given minimal time to adjust to each elastic condition, 2) the potential learning effect shown in the elastic conditions suggests that given more time to adapt, greater performance benefit may be achieved. 3) participants unfamiliarity with the test skates, 4) unknown interactions of the exoskeleton with protective equipment worn, 5) the need for a larger sample size to improve statistical power, and lastly, 6) these findings cannot be generalized to all ice hockey skating tasks.

Future directions for studies examining elastic assistance for ice hockey skating should examine how different skating tasks are affected by a similar system. While we can currently quantify the amount of force being stored and returned by the elastic elements, there are too many unknowns to exactly quantify how this force affects the hip joint. A future study could examine the change in passive hip moment caused by this system using a dynamometer. Physiological measures are also of interest, as if these systems are accompanied by a large increase in metabolic demands they may prove to be detrimental to performance over the course of a full hockey game. Conversely in they reduce metabolic cost as some exoskeleton systems have shown to do they could be invaluable. Additional joints should also be considered when developing systems to assist in the skating movement, as extending these systems to the knee and ankle may further benefit skating performance.

The implications of this study are large. This is the first study of its kind to introduce materials which store and return elastic energy to an athlete's body on ice. Based on the findings of this study, it stands to reason that this technology could be implemented into the protective equipment already worn by ice hockey players. This integration could improve the skating performance of athletes, however also based on these findings, the system would need to be tailored to each athlete individually in order to maximize their performance. This system has also shown promise in terms of reducing variability in knee movement while skating, whether or not this could lead to reduced injury rates in the future requires further study. As a first step, this study has shown that elastic systems of this type can be beneficial to performance, however the full extent of this benefit is still unknown. Based on the findings of this study, it appears that these benefits are a result of the system altering the cadence and step length of ice hockey players, and not the individual joint kinematics as was hypothesized. Future studies should examine the physiological effects associated with storing this elastic energy, as well as how the system affects different tasks required in a game of hockey.

Conclusion

This study examined the performance effects of a soft exoskeleton incorporating to offer elastic energy storage and return into ice hockey skating equipment. Kinematic, kinetic and perception data were collected on nine high calibre hockey players. This study demonstrated the feasibility of introducing soft exoskeletons to store and return elastic energy to an athlete's body while skating on ice. Several participants responded well yielding shorter skating start performance times. The system would need to be tailored to each athlete individually in order to maximize their performance. Further study is warranted with larger sample sizes, both male and female athletes, longer familiarization periods, and on different skating tasks.

Acknowledgements

The authors would like to thank Philippe Renaud and Phil Dixon for their help with data analysis and processing, as well as Aiden Hallihan, Neil MacInnis, Mike Solomon and Kristie Liu for their help during data collection.

THESIS CONCLUSION

This study contributes to two bodies of knowledge. Firstly, the further increasing understanding of externally valid on-ice biomechanics of ice hockey, and secondly to the development of systems which work in parallel with the human body to augment performance. A significant learning effect was shown when participants skated using the elastic assistance, where with each successive skating trial under the same elastic condition, acceleration performance improved. Despite this learning effect which suggests that true maximum performance changes were not achieved, differences in skating performance trended towards statistical significance.

The differences in skating acceleration measured by time to skate nine meters were not explained by changes in skating kinetics brought about by the elastic assistance. Instead, it appears that the elastic elements had an affect on the movement patterns associated with skating acceleration. While wearing the “Best Elastic” condition, stride length was decreased as was double support time. These reductions had no affect on the maximum velocity achieved during each stride, but the changes in performance times could be explained by the inclusion of a larger number of strides over a given distance compared to the control condition as a result of a shorter stride length. This is supported by the findings of Renaud (2017) where faster skaters exhibited shorter double support times than slower skaters.

The study was limited by a number of factors. Time constraints associated with ice arena rentals and the set up and take down of testing instrumentation meant that participants were given minimal time to adjust to each elastic condition. The learning effect shown in the elastic conditions suggests that given more time to adapt, measured changes in skating performance may have shown an even greater performance benefit. Participants were supplied with instrumented skates for the purposes of testing, and an unfamiliarity with these skates may have influenced skating kinematics, additionally the lack of protective equipment worn in the study compared to in a hockey game may also have affected participant comfort and therefore the kinematic measures. The study had a relatively small sample size of only nine individuals, given a larger sample size and an associated greater statistical power, results may have shown to be more significant. The results of the task performed cannot be generalized to ice hockey as a whole due to the differences in kinematics associated with repeated stopping and changes in direction which are present in a game of ice hockey.

Future directions for studies examining elastic assistance for ice hockey skating should examine how different skating tasks are affected by a similar system. Physiological measures are also of interest, as if these systems are accompanied by a large increase in metabolic demands they may prove to be detrimental to performance over the course of a full hockey game. Conversely in they reduce metabolic cost as some exoskeleton systems have shown to do they could be invaluable. Additional joints should also be considered when developing systems to assist in the skating movement, as extending these systems to the knee and ankle may further benefit skating performance.

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APPENDICES

Appendix A: Subject Consent Form

McGill

Participant Consent Form

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Effects of a Joint Stiffness Altering Equipment on Ice Hockey Skating Acceleration

Sponsor(s):

NSERC (CR DJP 45 3725-13) Fund # 238744 [Human factors analysis of ice hockey and equipment]

Bauer Hockey Corp. Fund # 238737

Purpose of the Study:
The purpose of this study it to examine the effects of altering joint stiffness on ice hockey skating acceleration. To examine this question, participants will skate in an exoskeleton designed to capture elastic energy and return it to the skating stride.

Your participation in this study involves:

1. Providing informed consent prior to the experimental session,
2. Providing data concerning your physical attributes, hockey experience, and hockey equipment usage (e.g. height, age, weight, number of years playing ice hockey, highest level played)
3. Performing vertical jumps both unassisted, as well as while wearing an exoskeleton system
4. Repeating a 15m long skating acceleration task under different amounts of added joint stiffness

5. Being recorded via a 3-dimensional Motion Capture camera set up.
6. It is anticipated that you will encounter no significant discomfort during these experiments. There is minimal risk associated with these experiments. You will be asked to wear a helmet before taking the ice.

Voluntary Participation*:*
Participation from the participant in the study is voluntary. The participant may refuse to participate in parts of the study, may decline to answer any question, and may withdraw from the study at any time, for any reason. If the participant decides to withdraw from the study, all the information collected from this participant will be destroyed, unless permission is given by the participant to keep it.

Potential Risks:
Participants will encounter no significant discomfort during the experiment. The tasks that the participant will be performing are basic hockey skills found in a regular ice hockey practice and games. Participants will be instructed to not look directly at the infrared LEDs on the Vicon cameras to avoid glare. No threat of harm to subject's vision exists.

Potential Benefits:
This research Study is to provide a base of knowledge for the development of new hockey equipment. This new equipment could be designed to improve skating performance. Additionally, Participants will gain a detailed 3-dimensional look at their skating stride in the acceleration tasks if they wish.

Compensation:
Participants will be given a $10 complimentary gift card for local restaurants for participation in the test protocol.

Confidentiality:
All personal information collected during the study concerning the participant will be encoded to preserve their confidentiality. These records will be maintained at the Biomechanics Laboratory by Dr. David Pearsall for 7 years after the end of the project, and will be destroyed upon the expiration of this time frame. Only members of the research team will be able to access them. In case of presentation, your personal information will remain completely anonymous. Video will be recorded during the study, however this video footage is solely for the use of the researcher, and will not be disseminated to the public without the express consent of the participant. In case of presentation, your personal information will remain completely confidential, unless you indicate in the agreement below that the researchers may identify you in the video-tape, if it is publicly disseminated.

If applicable, describe study options available to the participant using clear YES /NO options.

Yes:___No:____You consent to be photographed during testing.

Yes:___No:____You consent for the video-tape to be played publicly during the dissemination of results.

Yes:___No:____You can identify me in the video-tape if shown publicly:

Questions*:*
If you require information concerning the study (experimental procedures or other details), please do not hesitate to contact Brian McPhee at the address listed at the top of this document.

If you have any ethical concerns or complaints about your participation in this study, and want to speak with someone not on the research team, please contact the McGill Ethics Manager at 514-398-6831 or lynda.mcneil@mcgill.ca.

Please sign below if you have read the above information and consent to participate in this study. Agreeing to participate in this study does not waive any of your rights or release the researchers from their responsibilities. A copy of this consent form will be given to you and the researcher will keep a copy.

Participant's Name: (please print) ____

Participant's Signature: ______________________________________ Date: _____________

Appendix B: Pre-Testing Questionnaire

PRE-TESTING QUESTIONNAIRE

Name: ________________________________

Date of Birth: ________________________________

Hockey Experience (Years): ________________________________

Highest Level Played: ________________________________

Dominant Leg (Kick a ball): ________________________________

1. In the past year have you suffered a hip, knee or ankle injury which has prevented you from playing ice hockey? Explain.

   ____

   ____

   ____

2. Have you suffered any other lower body injuries in the last year? Explain.

   ____

   ____

   ____

3. Have you suffered a nervous system injury in the last year which has prevented you from playing ice hockey? (i.e. Concussion) Explain.

   ____

   ____

   ____

4. Are there any reasons that you don't believe you should be participating in this study? Explain.

   ____

   ____

   ____

Appendix C: Visual Analog Scale Questionnaire

Name: ______________________________________ **Condition** _________

Position: _________ **Years of Experience:** _________ **Age (yrs):** _________

Perceived acceleration

Slower than normal Normal Faster than normal

Comfort

Lowest Highest

Skating Power

Low Normal High

Resistance to mobility

Hard to move Normal Easier to Move

ADDITIONAL COMMENTS:

____

____

____

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Appendix D: Pugh Design Matrix for Elastic Assistance System Development

Matrix			**Cost**	**Ease of Adjustment**	**Individuality**	**Bulk**	**Number of possible variations**	**Total**
Exo type	***Soft***		+1	+1	+1	0	+1	4
	Hard		-1	-1	-1	-1	-1	-5
			Power contribution	**Supporting literature**	**Difficulty in design**	**Likelihood to get result**		
Joint focus	***Hip***		+2	+1	0	+1		4
	Knee		+1	+1	+1	+1		4
	Ankle		0	0	-1	0		-1
			comfort	**adjustment**	**individuality**	**Potential to slip**		
Attachment	***Equipment***		+2	-1	0	0		1
	Straps		-1	+1	+1	+1		3
			Time commitment	**Value of result**	**Enough by itself?**			
DV	***Time components (power) (acceleration)***		+1	+2	+1			+4
	Force		0	+1	0			+1
	EMG		0	+1	0			+1
	kinematics		-1	+1	0			0