DESIGN AND EVALUATION OF DYNAMIC KNEE ORTHOSIS SYSTEM FOR FEMALES WITH KNEE LIGAMENT INJURIES

A Thesis

Presented to the Faculty of the Graduate School

of Cornell University

In Partial Fulfillment of the Requirements for the Degree of

Master of Arts

by

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ABSTRACT

Knee ligament injury occurs frequently during athletic activities particularly for women and knee orthoses are often involved in post-injury management. A lightweight and aesthetically more acceptable Dynamic Knee Orthosis System (DKOS) is presented to females with a knee ligament injury (anterior cruciate ligament injury for example). The DKOS is embodied as a pair of close-fitting leggings with a detachable dynamic belt on the waist. DKOS can be used 1) to provide support for injured knee joint with lighter physical burden, 2) to restrict range of motion if needed, and 3) to assist regaining range of motion in post-surgical rehabilitation process. Statistical analysis of a series of biomechanical tests suggested that the proposed orthosis had less constraint on quadriceps muscles yet was less supportive than the commercial brace during running, triple hop and drop landing tasks. Subjective evaluation shows that 10 uninjured participants felt the proposed orthosis was more comfortable yet had same support as a commercial brace.

BIOGRAPHICAL SKETCH

Menglin Jia was born in Taiyuan, China on March 6, 1989, the daughter of Gaoyong Jia and Jinhui Yang. After graduating from Taiyuan Foreign Languages High School in 2007, she entered Hong Kong Polytechnic University and pursued a Bachelor of Arts degree in Fashion and Textile-Intimate Apparel division. She started to work in the fashion industry in Hong Kong right after graduation with Honors in 2011. Through valuable internships, full-time and freelance employment in Hong Kong and Mainland China, Menglin explored and took on the responsibilities of different job functions including market research, sales, sourcing, and design. From October 2012 to August 2015, Menglin worked as a lingerie designer with Triumph International Sloggi Asian team, researching current trends of intimate apparels and bringing new ideas to customers, while keeping the production costs at the lowest possible.

With function-oriented design innovation in mind, Menglin moved to the United States in August 2015 to pursue her Master of Arts in Apparel Design at Cornell University in Ithaca, NY. As a graduate student, she served as a teaching assistant for two classes regarding fashion, beauty and trends throughout history, as well as a research assistant for several faculty research projects. Menglin will continue her studies in functional apparel design as a PhD student at Cornell University in the fall of 2017.

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CHAPTER 1

INTRODUCTION

1.1 Motivations

1.1.1 Knee joint injury. The knee joint injury is one of the most common sports-related injuries. It accounts for 39.8% of sports injuries (Majewski, Susanne, & Klaus, 2006), and 15.2% among high school young athletes (Ingram, Fields, Yard, & Comstock, 2008). Females were reported to have higher risk of knee joint injuries compared to male (Loes, Dahlstedt, & Thomee, 2000).

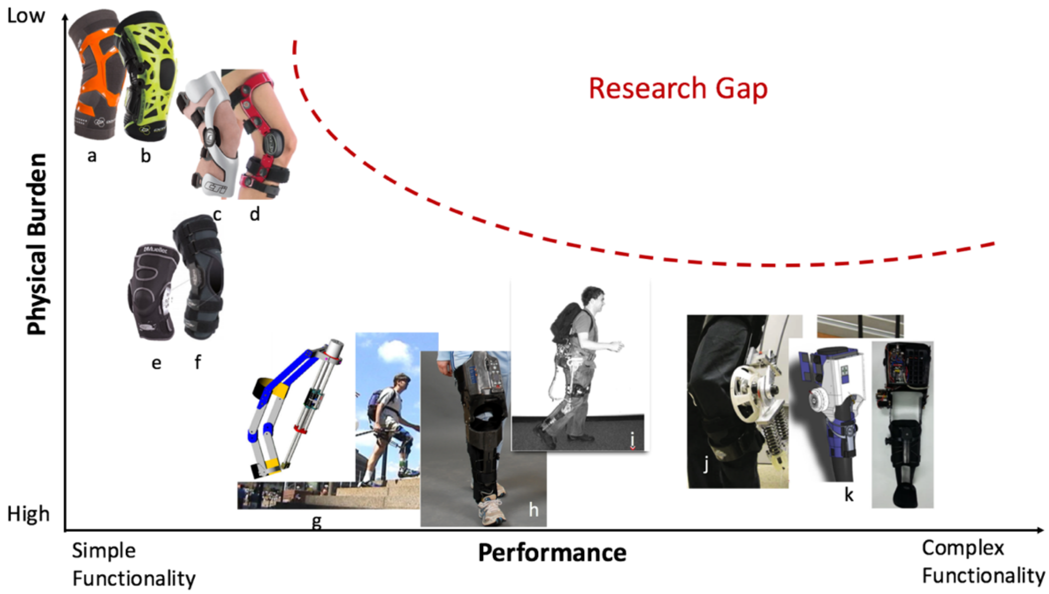
Knee joint injuries often involve disruption of one or more knee ligaments which are fibrous connective tissues connecting the femur and the tibia. The most frequently injured ligament is the anterior cruciate ligament (ACL) (Boden, Dean, Feagin, & Garrett, 2000; Hewett, 2006). This injury may lead to posttraumatic laxity and immediate functional impairment, but also can increase the long term risk of developing knee osteoarthritis (OA) (Kannus & Järvinen, 1989; Daniel et al., 1994). There are 32,000–320,000 people suffered from ACL injuries in the United Stated every year (assuming the current approximate population is 320 million) (Murray, Vavken, & Fleming, 2013). Some study even claimed that the number of the injury per year is as high as 400,000 in the USA (Junkin et al., 2009). Females have four to six times higher risk of ACL injury than males performing the same cutting and landing sports (Arendt & Dick, 1995; Hewett, 2006).

1.1.2 Knee Orthosis. Knee brace prescription is a common practice for knee joint injurie, although no clear scientifically proved benefit has been reported in the literature. 63% of surgeons prescribe knee brace use to their ACL reconstruction patients and 71% of them ask their patients to use brace for up to one year (Delay, Smolinski, Wind, & Bowman, 2000). Knee braces, or knee orthoses, are passive or active mechanical devices that help restore the functionality of the knee joint. It is usually used together pre-operatively and post-operatively with functional electrical stimulation and physical therapy (Krebs, Hogan, Durfee, & Herr, 2006; Maciejasz, Eschweiler, Gerlach-Hahn, Jansen-Troy, & Leonhardt, 2014).

Patients with knee ligament injuries often reported benefits of wearing knee orthoses. These positive subjective feedbacks of bracing included increasing knee stability and athletic performance, improving confidence and decrease pain during daily life activities (Beynnon et al., 1992a; Cawley, France, & Paulos, 1991a; France & Paulos, 1994; Kramer, Dubowitz, Fowler, Schachter, & Birmingham, 1997a; Paluska & McKeag, 2000). One study even claimed that knee brace was accepted clinically mainly due to its subjective performance (Martin, 2001). However, the stated subjective benefits have been failed to be verified by scientific investigation. There is lack of scientific evidence on the physio aspect of bracing, such as if braces are helpful at level required for athletic participation (Beynnon et al., 1992a; Cawley et al., 1991a; France & Paulos, 1994; Kramer et al., 1997a; Martin, 2001; Paluska & McKeag, 2000).

In spite of the positive subjective feedbacks of knee bracing, patients also complained about fit, slippage and discomfort of knee brace (McDevitt et al., 2004). Knee brace acts as an additional layer wrapping and forming a snug fit around the knee joint. The interface usually composed of a layer of elastic material, usually neoprene.

The extra physical burden, including extra weight, bulkiness, comfort and fit, need to be considered during design process.



a. Webtech Knee Brace ("The Technology Behind Webtech Knee Braces | DonJoyPerformance.com," n.d.)
b. Trizone Knee Support ("DonJoy Performance TriZone Knee Support | DonJoyPerformance.com," n.d.)
c. CTi Custom Knee Brace ("CTi Custom," n.d.)

d. Defiance III Custom Knee Brace ("Defiance III Knee Brace | DJO Global," n.d.)
e. HG80® Premium Hinged Knee Brace ("Mueller Premium Hg80 Hinged Knee Brace," n.d.)
f. Playmaker II Knee Brace CTi Brace ("DonJoy Playmaker II | DJO Global," n.d.)
g. Robo-Knee (Pratt, Krupp, Morse, & Collins, n.d.)
h. Tibion® PK100 bionic leg orthosis (Horst, 2009)
i. Quasi Passive Knee (Walsh, Endo, & Herr, 2007)
j. Assist-On Knee (Celebi, Yalcin, & Patoglu, 2013)
k. Knee exoskeleton with Foot Pressure and Knee Torque Sensor (J. H. Kim et al., 2015)

Figure 1.1 Current designs of knee orthosis research gap.
Physical burden includes extra weight, bulkiness, thermal & tactile comfort and fit.

Developmental effort for improved knee orthoses design have been made both in the industry and academia. Orthoses developed in academia usually provided more functionalities than commercial knee braces (Celebi et al., 2013; Dollar & Herr, 2008; Horst & Marcus, 2006; J. H. Kim et al., 2015; Pratt, Krupp, Morse, & Collins, 2004). Additional electro-mechanical devices of the orthoses offer the added functionalities yet increase the physical burden at the same time. Figure 1.1 summaries selected examples of knee orthoses according to their physical burden and performance. There is a critical need for lightweight and highly functional knee orthoses.

1.2 Objectives

Knee injury is an injury that occurs frequently during athletic activities particularly for women and knee braces are often involved in post-injury management (Boden et al., 2000; Hewett, 2006). Knee orthoses are worn as an extra layer on the injured leg. The interface of knee braces and the placement of electro-mechanical devices are the possible reasons for the research gap stated at Figure 1.1. Improving the interface while maintaining the supporting functions of knee brace can be one possible solution. Leggings with hinges is proposed as an interface alternative for females.

Continued advances in technological development makes functional clothing design a more interdisciplinary endeavor and opens more design opportunities in apparels. Contemporary “smart” garments have many functions for wellbeing, including “sensing, actuating, powering, generating, storing, communicating, data processing and connecting with both body and environment.” (Farrer, 2014). A detachable dynamic belt, or “smart” belt on the waist was proposed as a complement to the leggings with hinges. The dynamic belt was designed to enhance the performance of the proposed orthoses system, specifically to assist regaining range of motion (ROM) in post-surgical rehabilitation process of the knee joint.

This study presents an alternative design solution to a knee orthosis to assist people with knee ligament injuries (anterior cruciate ligament injuries, for example). Specifically, a powered lightweight and portable knee orthosis will be developed, which improves the stability, assists rehabilitation, enhances mobility of injured knee in daily life and sports activities.

The specific objectives of this study are list as follows:

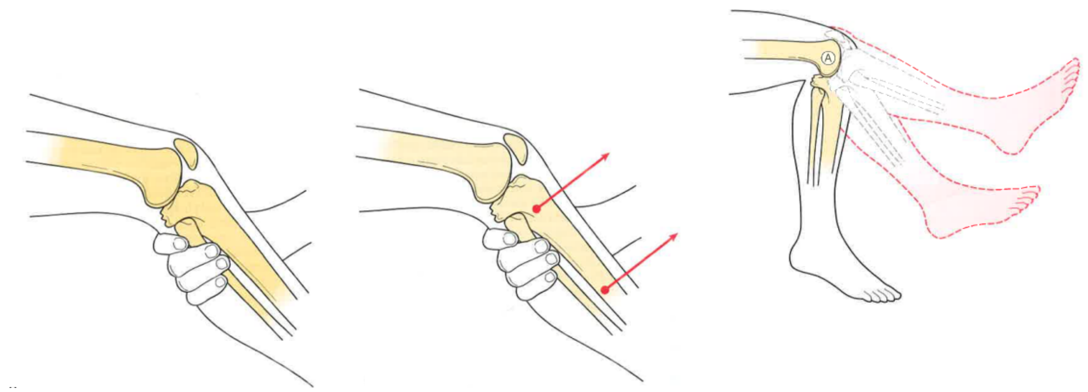
1) to develop a light and portable knee orthosis two hinges at right leg in the form of a legging, which could improve the physical burden issues of current braces;
2) to develop a dynamic belt system with control system capable of assisting knee rehabilitation process.

CHAPTER 2

LITERATURE REVIEW

2.1 Knee Ligament Injuries

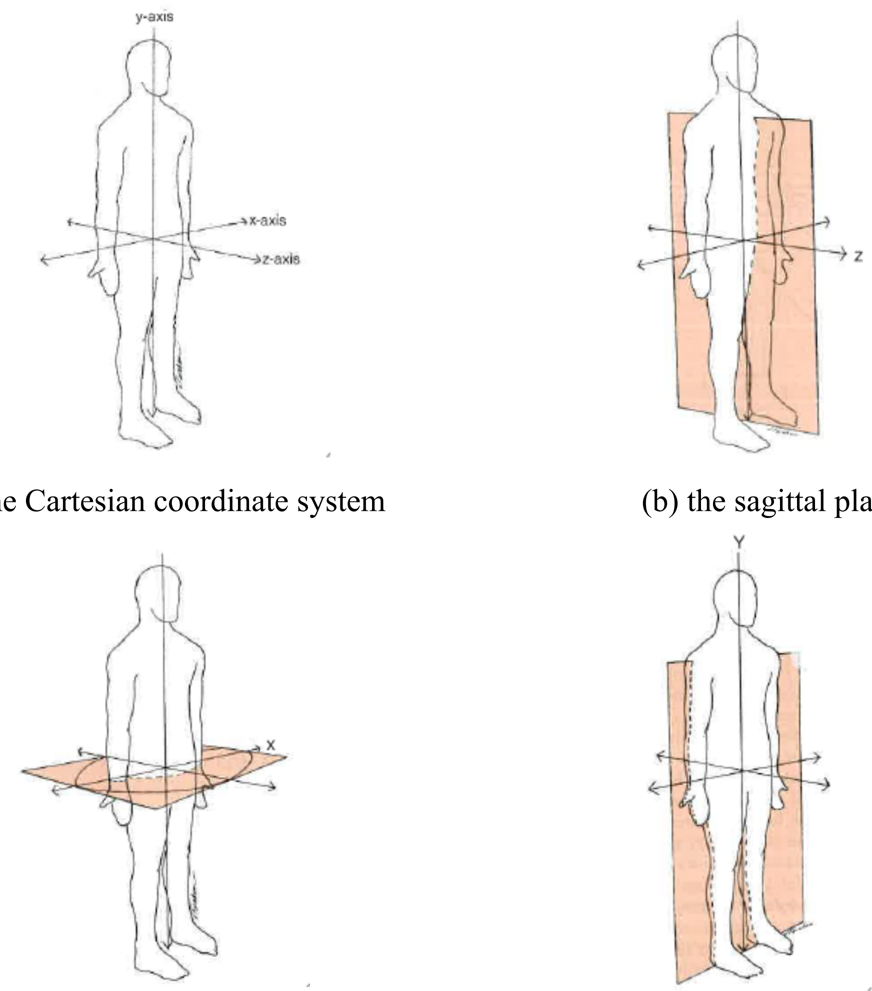
2.1.1 Kinematics and kinetics. Kinematics and kinetics are foundational concepts in biomechanics. Kinematics describes the displacement without considering the forces and moments that cause that movement. Kinetics calculates the force and moments that cause body motions. It is important to understand terminology related to describing human body motions and moments before diving into knee anatomy and functions.



(a) Translatory motion (b) Translatory motion (c) Rotary Motion

Figure 2.1 Examples of two types of displacement
(a, b): standard anterior drawer Test for ACL integrity. Adapted from "Joint structure and function: a comprehensive analysis" by Levangie, P. K., & Norkin, C. C., 2011, Copyright © 2011 by F.A. Davis

The human skeleton acts as a system of levers and segments which constrained by ligaments, muscles, and other bony forces during movements (Levangie & Norkin, 2011). General body movements are achieved by combining two basic types of motions, namely translatory and rotary movements. Translatory motion (or linear displacement) happens when a body segment move in the direction of a straight line. Rotary motion occurs when a body segment move around an axis (Figure 2.1). Pure translatory or rotary motion rarely occurs in human motions without each other.



(a) the Cartesian coordinate system

(b) the sagittal plane

(c) the transverse plane

(d) the frontal plane

Figure 2.2 Body in anatomic position, showing the Cartesian coordinate system (x-axis, y-axis, z-axis represent the coronal axis, vertical, and anteroposterior axis respectively and three planes. Adapted from “Joint structure and function: a comprehensive analysis” by Levangie, P. K., & Norkin, C. C., 2011, Copyright © 2011 by F.A. Davis

Body movements occurs in a space commonly described by Cartesian coordinate system. The intersection, or the origin of three axes (the x-axis, y-axis and z-axis), is located at center of mass of the human body, if the body is in anatomic position (Figure 2.2a). Rotary motions not only can be described as appearing around one of three axes, it could also take place in or parallel to one of three planes, specifically sagittal plane, transverse plane, and frontal plane (Figure 2.2 b, c, d).

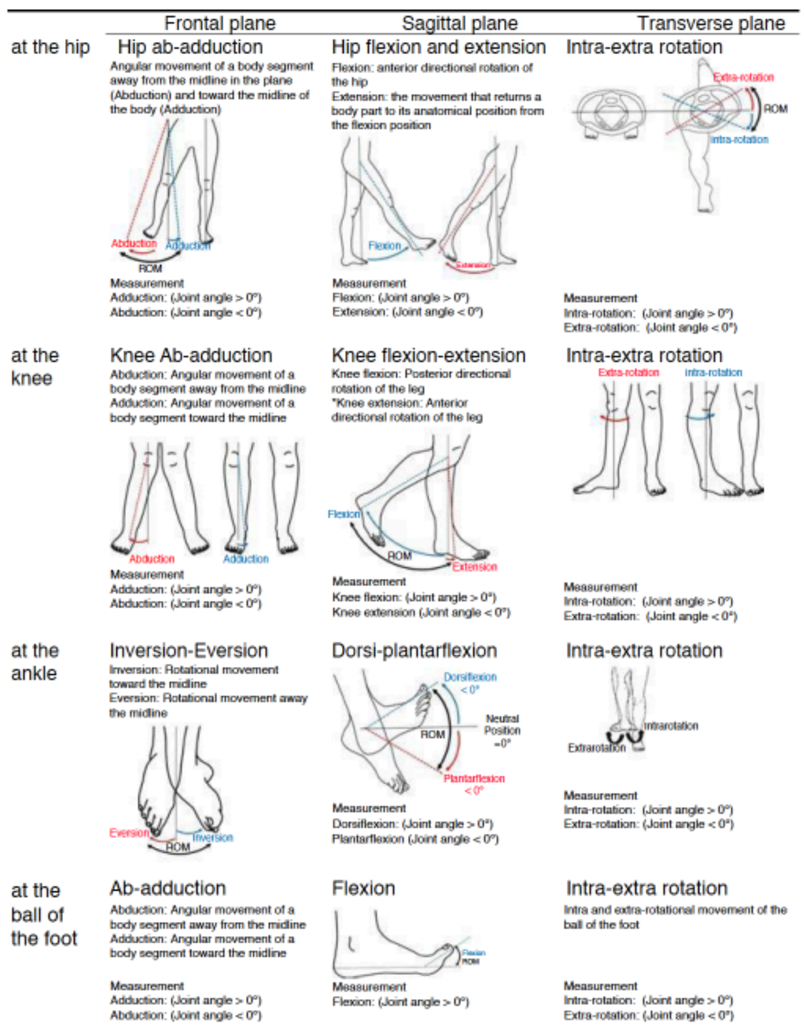


Figure 2.3 Lower body movements terminology. Adapted from "Impact of firefighter gear on lower body range of motion" by Park et al., 2011, *International Journal of Clothing Science and Technology*, *27*(2), 315–334, Copyright © 2015 by Emerald Group Publishing Limited

Figure 2.3 (Park et al., 2015) describes lower body movements terminology, including hip, knee and ankle joints, with measurement of range of motion (ROM) at each joint.

Kinetics refers to the study of rotary and translatory forces and moments. Various forces act on joint, such as muscular forces, external forces (for example, gravitational forces), and joint reaction forces. Moment of force, or torque, describes "the strength of rotation" produced by forces. Its magnitude is the product of magnitude of force and the perpendicular distance between forces. Its direction can be described according to the corresponding joint motion(Levangie & Norkin, 2011). Joint moment studied in this thesis is defined as the internal moment muscles produced to counteract the external moment.

2.1.2 Knee anatomy and functions. Knee is one of the largest and most often injured joints in human body. The knee joint plays an important role in transmitting, absorbing and redistributing body weights and forces, and in maintaining stability and mobility of human body with minimum energy consumed (Masouros, Bull, & Amis, 2010). It disperses varies forces from muscles, ligaments and weight-bearing forces such as gravity. Any change to the knee joint anatomy will have consequential influence on knee functions. Therefore, it is essential to understand the anatomy of the knee joint.

Knee has most complex structure than any other two lower body joints (hips and ankle joints). Knee is composed of two different separate joint structures, namely the tibiofemoral joint and the patellofemoral joint (Figure 2.4) (Masouros et al., 2010).

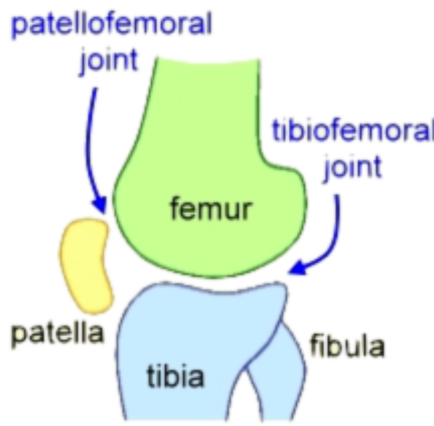


Figure 2.4 Right knee complex (medial view). Adapted from "(i) Biomechanics of the knee joint" by Masouros et al., *Orthopaedics and Trauma*, *24*(2), 84–91 Copyright © 2010 by Elsevier Ltd.

The tibiofemoral joint connects the thigh bone (femur) and the shin bone (tibia) by menisci and knee ligaments. The anterior cruciate ligament (ACL), a fibrous connective tissue, connects lateral femoral condyle to the anterior portion of the tibial plateau (Murray et al., 2013). This ligament is one of four primary stabilizing ligaments of the knee, specifically lateral collateral ligament (LCL), medial collateral ligament (MCL), posterior cruciate ligament (PCL) and anterior cruciate ligament (ACL). These four ligaments act as "strings" connecting femur and tibia. The ACL is termed a "cruciate" ligament because it creates a cross together with PCL in the posterior of knee. (Figure 2.5) (Murray et al., 2013). Similarly, the patellofemoral joint is also composed of bones (patella and femur), varies ligaments and tendons, and neuromuscular system (Y.-M. Kim & Joo, 2012). ("Common Knee Injuries-OrthoInfo - AAOS," n.d.)

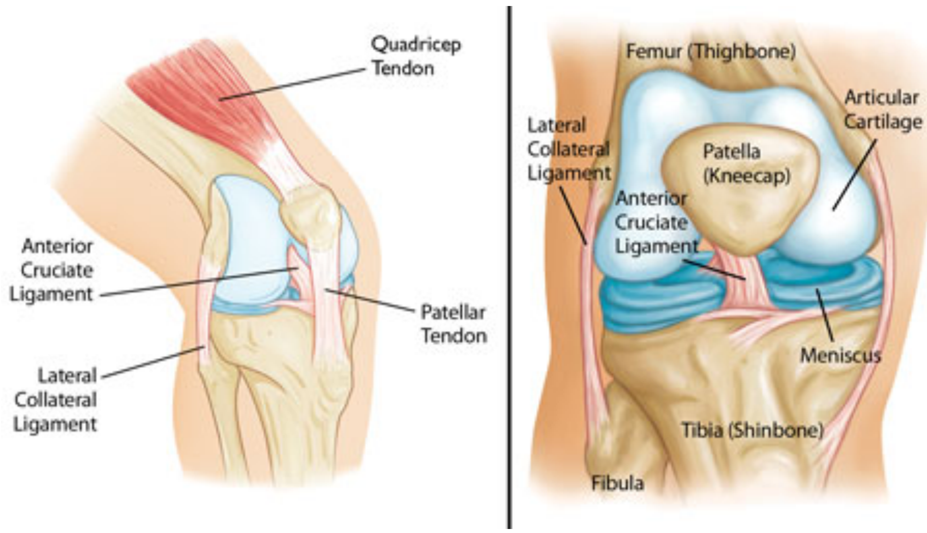


Figure 2.5 Normal knee anatomy (three quarter view and front view) Adapted from Common Knee Injuries-OrthoInfo - AAOS. (n.d.). Retrieved April 25, 2016 from http://orthoinfo.aaos.org/topic.cfm?topic=a00325

Knee ligaments are indispensable for the knee complex. They act as major stabilizers. The ACL and PCL maintain stability to not only the anterior and posterior motion, but also internal and external rotation of the joint. The side-to-side stability was maintained by MCL and LCL (Levangie & Norkin, 2011). Table 2.1 summaries functions of knee ligaments in terms of straight plane movement.

Table 2.1

Functions of knee ligaments

	Structures	Function
Anteroposterior/Hyperextension Stabilizers	Anterior cruciate ligament	Limit anterior tibial (or posterior femoral) translation
	Posterior cruciate ligament Meniscofemoral ligaments	Limit posterior tibial (or anterior femoral) translation
Varus/valgus Stabilizers	Medial collateral ligament Anterior cruciate ligament Posterior cruciate ligament Arcuate ligament Posterior oblique ligament	Limit valgus of tibia
	Lateral collateral ligament Anterior cruciate ligament Posterior cruciate ligament Arcuate ligament Posterior oblique ligament	Limit varus of tibia
Medial/lateral Rotational Stabilizers	Anterior cruciate ligament Posterior cruciate ligament Meniscofemoral ligaments	Limit medial rotation of tibia
	Medial collateral ligament Lateral collateral ligament	Limited lateral rotation of tibia

Normal intact knee ligaments provide knee stability which allows motion in six degree of freedom. Table 2.2 describe these motions with respective range of motion (Masouros et al., 2010).

Table 2.2

Three rotation and three translation in knee joint

Motions	Range of Motions
Extension – Flexion	-5 ~ 0 ~ 160 degrees
External – Internal Rotation	25 ~ 30 degrees (in flexion)
Varus – Valgus Rotation	6 ~ 8 degrees (in extension)
Anterior – Posterior	5 ~10 mm
Medial – Lateral	1 ~ 2 mm
Compression – Distraction	2 ~ 5 mm

Any alteration of knee structure could contribute to joint instability and altered kinematics. A complete ACL rupture, for example, may result in significant posttraumatic laxity, functional disability, and premature onset of arthritis of the knee (Daniel et al., 1994; Kannus & Järvinen, 1989; McDaniel Jr & Dameron Jr, 1983; Noyes, Mooar, Matthews, & Butler, 1983). "Rule of Third", first pointed out by Noyes et al. in 1983, is used to describe how patients with an ACL-deficient knee compensate their activities in daily lives. The study reported that approximately one-third of patients compensated adequately and was able to return to competitive or recreational activities without limitations. And one-third of patients compensated but sports activity choices were limited. The remaining one-third of patients performed poorly because of persistent pain and swelling and required reconstructive surgery (Noyes et al., 1983).

2.1.3 Treatment of knee ligament injuries. There are wide range of knee ligament injuries, due to the complexity of knee structure and functions. Severity of the injuries may be different as well. The treatments, therefore varies from the conservative nonsurgical method, to reconstruction surgeries (Müller, 1996).

Patients receiving nonsurgical treatment need to immobilize their injured knee in a plaster cast for six weeks, and go through a progressive muscular rehabilitation program (Pompe, 1979). Reconstruction surgery methods, on the other hand, are performed differently for different ligament injuries. The goals of surgical treatments are to reconstruct knee ligaments anatomically and to provide long-term knee stability. For example, effort of developing reconstructive treatment of ACL tear has been made since 1895. The current "Gold Standard of Treatment for skeletally mature patients", described by Murray at al. (Murray et al., 2013), employs surgical method to reconstruct the ACL with a tendon graft which could be choose from autograft or allograft. However, even this gold standard cannot prevent the sequelae of ACL injury unfortunately (Murray et al., 2013).

2.1.4 Knee rehabilitation. Regardless of surgical or nonsurgical treatment, people with knee ligament injuries need rehabilitation. Rehabilitation often involves a series of perioperative physical therapy sessions. Length and procedures of knee rehabilitation is dependent upon the nature of the injuries (Irarrázaval, Yaseen, Guenther, & Fu, 2017). Yet all physiotherapy sessions are progressive toward returning normal daily activities and exercises. Repeated and routine lower body movement with assistant and observation of a physiotherapist is often included in knee rehabilitation program.

Such treatments could help to restore range of motion of the knee joint, to reduce pain and edema, and to regain strength and endurance of muscles. (Irarrázaval et al., 2017; Pompe, 1979).

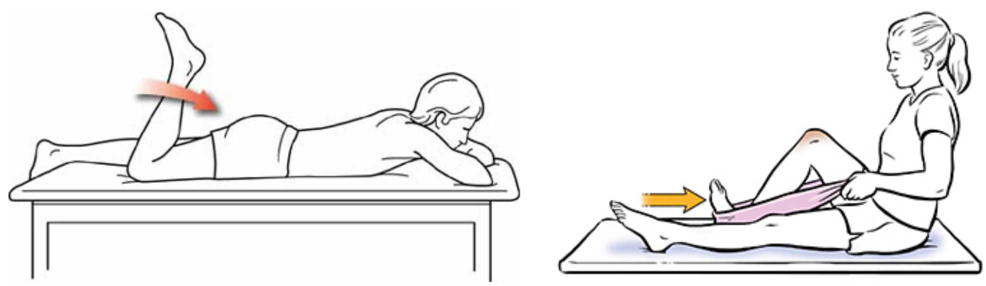
Knee range of motion (ROM) exercises after immobilization at extension or restricted movement (less than 90 degree) begins as soon as a surgeon permits. Otherwise patients may develop scar tissue (arthrofibrosis) and full ROM will be restricted. Arthrofibrosis is a potential complication and often occurs after surgery (Shelbourne, Patel, & Martini, 1996). Table 2.3 describes current knee ROM exercises, including both extension and flexion exercises (Fisher & Shelbourne, 1993; Shelbourne et al., 1996). The final goal of these exercises is to restore full ROM symmetric to the contralateral knee (Yabroudi & Irrgang, 2013). Table 2.4 indicates standards for the optimal results of ROM rehabilitation according to the International Knee Documentation Committee (IKDC) ("Passive extension | KNEEguru," n.d.)

Table 2.3

Knee range of motion (ROM) exercises

ROM Exercises	Detail
Flexion exercise	wall slides prone knee flexion (Figure 2.6a) heel slides (Figure 2.6b) stationary bicycle riding with progressive lowering of the seat therapist assisted flexion device assisted flexion (Flex-seat, CPM)
Extension exercise	weighted prone hangs passive extension (straightening)

therapist assisted extension



(a) Prone knee flexion (b) Heel slide

Figure 2.6 Knee flexion exercise. (a) Adapted from Prone Knee Flexion. (n.d.). Retrieved June 3, 2017, from https://www.spine-health.com/fig-3-prone-knee-flexion (b) Adapted from Leg Muscle Stretches: Knee Flexion - Fairview Health Services, (n.d.). Retrieved June 3, 2017, from https://www.fairview.org/healthlibrary/Article/84833

Table 2.4

International Knee Documentation Committee (IKDC) criteria for the evaluation of range of motion in the reconstructed knee compared with that of the opposite knee

IKDC rating	Extension	Flexion
Normal	≤2°	≤5°
Near normal	3°–5°	6°–15°
Abnormal	6°–10°	16°–25°
Severely abnormal	>10°	>25°

Pain and edema treatment, along with muscular rehabilitation are equally important as ROM exercises. An clinically proved effective method to reduce pain and swelling is cryotherapy (van Grinsven, van Cingel, Holla, & van Loon, 2010; Yabroudi & Irrgang, 2013). Cryotherapy is defined as use of cold, in any form such as icepack and ice whirlpool, for certain amount of time each day (Hocutt, Jaffe, Rylander, & Beebe, 1982). As for muscular rehabilitation, it involves strengthening lower body muscles and regaining neuromuscular control while minimizing graft strain. The goal of muscular rehabilitation is to achieve full weight-bearing and to return to normal daily activities.

2.2 Design Effort for Knee Rehabilitation

Design effort to improve knee rehabilitation has been made intensively in both industry and academia. Both unpowered and powered devices and their effect will be discussed in this section.

2.2.1 Unpowered device. Devices without external power source are defined as unpowered devices in this study. Knee braces and continuous progressive movement (CPM) machines are two unpowered devices which are commonly used during knee rehabilitation process.

Knee braces, or orthoses are often involved during treatment for knee ligament injuries. The word "orthoses", a general term for brace and splints nowadays, originated from Greek orthōsis for "straightening". Orthoses play an essential role in rehabilitation. Depending on the structure, orthoses could "guild motion, bear weight, align body structures, protect joints or correct deformities" (Krebs et al., 2006).

Figure 2.7 summaries commonly used brace available on the market. No difference between off-the-shelf and custom braces have been found by literature (Beynnon et al., 1992b).

Use of knee braces should complement, not compromise patients' movement range, unless the brace is supposed to limit the ROM or to improve the stability of soft

Manufacturer	Model	Cost ($)[a]	Material	Design highlights	Recommended usage	Custom/ OTS
Albrecht	Jack ACL	1,300.00	Aluminum	Constant posterior-directed translation force, 15 adjustable levels of spring tension	Activities of daily living	OTS
Bledsoe	AXIOM-D	569.99	Steel-reinforced aluminum	Dynamic tibial mechanism, migration preventing strap system	High impact activities	Both
			Lightweight magnesium material	Dynamic tibial mechanism, migration preventing strap system	Activities of daily living and athletic activities	Both
	Z-12 D	529.99	Lightweight magnesium material	Dynamic tibial mechanism, lightweight/low profile, migration preventing strap system	Activities of daily living and athletic activities	Both
Breg	Fusion	499.99	Aluminum	AirTech™ frame pads, pivot point strap tabs, ProForm medial structure technology	Activities of daily living and athletic activities	Both
	LPR	489.99	Aluminum	AirTech™ frame pads, truss-shaped frame for high strength-to-weight ratio	Activities of daily living and athletic activities	Both
	X2K	479.99	Aluminum	Diamond design for varus–valgus stiffness	Activities of daily living and athletic activities	Both
DonJoy	Defiance	899.99	Carbon composite	4-points-of-leverage system™, FourcePoint™ hinge technology	Activities of daily living to high impact activities	Custom
	Armor	549.99	Aluminum	4-points-of-leverage system™, FourcePoint™ hinge technology, steel-reinforced hinge plate	High impact activities and extreme sports	OTS
	FULLFORCE™	524.99	Aluminum	4-points-of-leverage system™, FourcePoint™ hinge technology	Athletic activities	OTS
Össur	CTi®	399.99	Carbon composite	Total support system™, accutrac® hinges, Sensil® padding	Medium to high impact activities	Both
	Paradigm®	402.99	Carbon composite	Flexible subshell, polycentric hinges	Low to medium impact activities	Both
	MVP® contour	402.99	Aluminum	Flexible subshell, accutrac® hinges, sensil® padding	Activities of daily living and athletic activities	OTS
Townsend	Premier	624.00	Carbon graphite	Townsend motion TM5 + hinges, synergistic suspension strap, anti-migration padding	Activities of daily living and athletic activities	Custom
	Air	650.00	Carbon graphite	Townsend motion TM5 + hinges, synergistic suspension strap, anti-migration padding, anti-rotation tibia shell bolster	High impact activities and extreme sports	Custom
	Rebel	549.99	Aluminum	Townsend motion TM5 + hinges, synergistic suspension strap, anti-migration padding	Activities of daily living and athletic activities	Both

Figure 2.7 Summary of commercially available functional braces that commonly prescribed for ACL injury rehabilitation. Adapted from "Functional bracing of ACL injuries: current state and future directions" by Smith, S. D., LaPrade, R. F., Jansson, K. S., Årøen, A., & Wijdicks, C. A., *Knee Surgery, Sports Traumatology, Arthroscopy*, *22*(5), 1131–1141 Copyright © 2013 by Springer-Verlag Berlin Heidelberg

tissue (Khazaie, Saeedi, & Vahab-Kashani, 2017). Functional knee braces have been reported to use for the following purposes:

- to prevent excessive strain on the healing graft and to stabilize the knee joint after surgery (Beynnon et al., 1992b; Birmingham et al., 2008; McDevitt et al., 2004; Risberg, Holm, Steen, Eriksson, & Ekeland, 1999; Wojtys, Kothari, & Huston, 1996)
- to prevent potential injuries and further damage to meniscus and to support the knee joint either before surgery or for non-operative treatment (Delay et al., 2000; Logerstedt, Lynch, Axe, & Snyder-Mackler, 2013);
- to prevent subsequent injuries for skeletally immature patients before the reconstruction surgery can be performed without compromising the physis (epiphyseal growth plate) (Moksnes, Engebretsen, & Risberg, 2012).

Continuous Passive Motion (CPM) is widely applied in the field of orthopedic rehabilitation. By using of a passively controlled mechanical device, patients can move their knee joints passively in a certain range of motion in a slow and continuous manner (Gose, 1987). Figure 2.8 illustrates one such device for CPM. As achieving full ROM is one of the key factor in knee rehabilitation (Kisner & Colby, 2012), CPM is shown to have following beneficial effects:

- It assists patient to achieve earlier and bigger range of motion, thus reduces the length of hospital stays (Beaupre, Davies, Jones, & Cinats, 2001);
- It helps patient to overcome the side effects of immobilization, for example muscle strength loss and atrophy (O'Driscoll & Giori, 2000; Peterson, 1977);
- It enhances wound healing and venous flow after surgical treatment (Lynch et al., 1984);

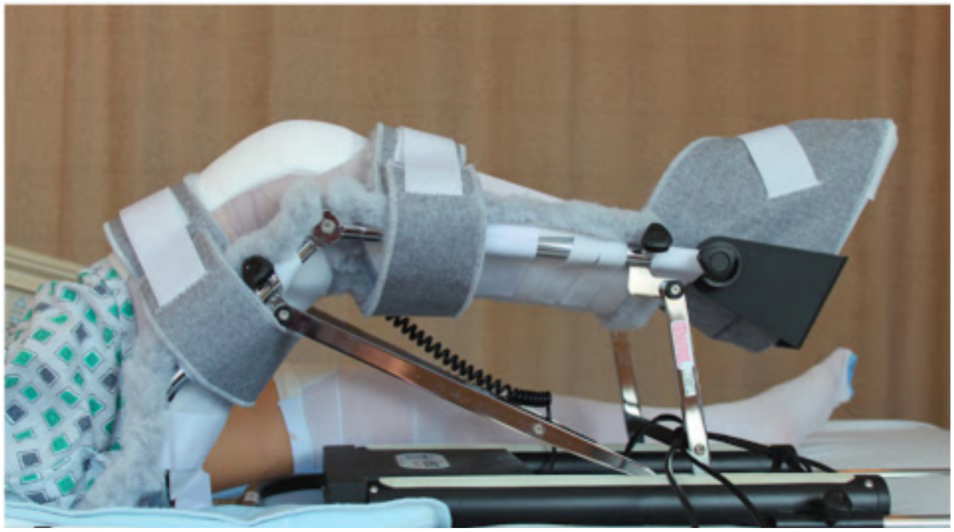


Figure 2.8 Continuous motion devices for the knee joint Adapted from "Therapeutic exercise: foundations and techniques". by Kisner, C., & Colby, L. A., 2012, Copyright © 2012 by F.A. Davis

2.2.2 Powered device. Powered (active) devices utilize external power either through wall outlet or battery. There is an increasing trend for such devices to utilize robotic technology. Robotic technology is beneficial to orthopedic rehabilitation. It was shown that robotic-aided therapy has advantageous influence on restoring ROM of injured joint (Prange, Jannink, Groothuis-Oudshoorn, Hermens, & IJzerman, 2006). Standard rehabilitation process is labor-intensive and require physiotherapist constant supervising. Robotic technology could potentially transform rehabilitation process to technology-assisted and task-specific operation, thus simplify the protocols and lower the cost. Furthermore, data obtained from the automated operation could be analyzed to help future diagnosis, protocol customization and personal record maintenance (Jamwal, 2011).

Robotic devices have been actively developed for knee rehabilitation in forms of exoskeletons and orthoses. Exoskeletons and orthoses are the same device with different target users. Hugh Herr defined both terms as “mechanical devices that are essentially anthropomorphic in nature, are 'worn' by an operator and fit closely to the body, and work in concert with the operator's movements”. Exoskeletons are typically used by an able-boded person to augment his/her physical abilities, while orthoses refer to devices that assist for patients with limb pathology (Herr, 2009).

Figure 2.9 RoboKnee, a one degree of freedom exoskeleton. Adapted from “The RoboKnee: an exoskeleton for enhancing strength and endurance during walking” by Pratt et al, In *Robotics and Automation, 2004. Proceedings. ICRA’04. 2004 IEEE International Conference on* (Vol. 3, pp. 2430–2435). IEEE. Copyright © 2004 by IEEE

RoboKnee is a one degree of freedom exoskeleton (Figure 2.9). With the help of a low impedance series elastic actuators, the RoboKnee provides power to the knee during stair climbing and squatting with heavy load. This device determines user’s intent through two load cells inside user’s shoes. Two load cells receive the ground reaction force and the knee joint ankle. Torque is then applied to the knee according to the information captured by the two load cells. Yet one biggest disadvantage, according to the authors, is that user cannot sit down when wearing the RoboKnee, since the device is placed behind the leg. (Pratt et al., 2004)

Other methods were explored to capture user's intent. EMG-based knee exoskeleton (Figure 2.10), developed by Berlin University, utilized EMG signal to decide user's intended motion (Fleischer, Reinicke, & Hommel, 2005). A lightweight (3.5kg) polycentric knee exoskeleton was developed by J.H Kim et al. (Figure 2.11). Foot pressure and knee torque sensors are used to determine user's intention. This device mimics polycentric motion of human knee joint, while minimizes total weight (J. H. Kim et al., 2015).

Figure 2.10 EMG-based knee exoskeleton. Adapted from "Predicting the intended motion with EMG signals for an exoskeleton orthosis controller". *In Intelligent robots and systems, 2005.(IROS 2005). 2005 IEEE/RSJ international conference on* (pp. 2029–2034). IEEE. Copyright © 2005 by IEEE

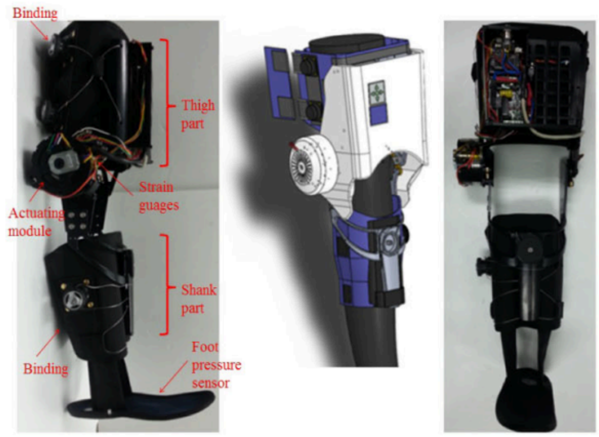


Figure 2.11 Polycentric knee exoskeleton robot. Adapted from “Design of a Knee Exoskeleton Using Foot Pressure and Knee Torque Sensors” by J. H. Kim et al. *International Journal of Advanced Robotic Systems*, Vol. 12, Issue 8, 2015.

A spring-attached knee exoskeleton developed at Massachusetts Institute of Technology (M.I.T.) (Figure 2.12) has a similar mechanical concept as the RoboKnee. This exoskeleton was designed specifically for running tasks. The device is composed of a knee brace and a spring in parallel to the user’s knee joint. Unlike the RoboKnee, this device does not provide extra torque to the knee joint. The spring stores and releases energy during gait, thus reduces metabolic cost during running. (Dollar & Herr, 2008)

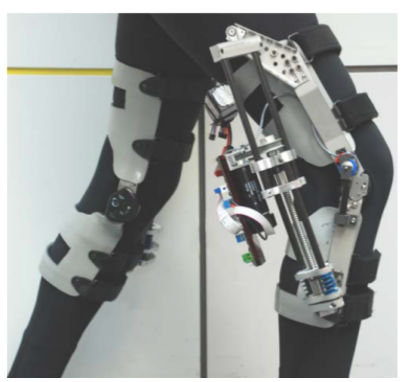


Figure 2.12 Quasi-passive knee exoskeleton to assist running. Adapted from “Design of a quasi-passive knee exoskeleton to assist running” by Dollar, A. M., & Herr, H., In *Intelligent Robots and Systems, 2008. IROS 2008. IEEE/RSJ International Conference on* (pp. 747–754). IEEE. Copyright © 2008 by IEEE

2.3 Apparel Design for Wellbeing

Clothing began to be regarded as a rehabilitative tool in the 1930s. Donning and doffing processes were observed by medical staffs in hospitals for cerebral palsied children, in order to improve physical and cognitive skills (Hoffman, 1979). The 1940s witnessed a change on disability research from focusing on dependence to promoting independence, and clothing was regarded as an essential part of this initiative (Dillingham, 1948). In the 1950s, fashion designer Helen Cookman designed a line and a self-help booklet "Functional Fashions for the Physically Handicapped" (Cookman, 1961).

In the 1960s, research initiatives continued to focus on self-help for disabled people, as detailed pattern design brochures and advice handbooks for dressing, grooming and altering ready-to-wear clothing were published. In 1973, the Rehabilitation Act (the "Rehab Act") was passed by the US congress, giving a boost to research, addressing both disabled individuals and their caregiving support personnel. More and more literature since the 1970s started to place emphasis on clothing appearance and visual impact of people with disabilities, adding a psychological component to the design process. Research attention started to turn towards fashionable clothing from adaptive clothing.

Despite of decades of applied research information since the 1930s, design solutions for the disabled and injured are still not available to individuals from the mass market. Very few companies design, manufacture and sell fashion for the physically challenged. This study only found one brick-and–mortar retail place in Toronto, which is the “IZ Adaptive” founded by Izzy Camelleri. A small number of specialized retailers, for example, Xeni Collection, Rolli-Moden and Silvert’s Adaptive Clothing, IZ Adaptive, offer products through online and catalogue channels. The garments range from functional to more fashion-oriented. Carroll and Kincade indicated that few mainstream retailers regarded consumers with physically-challenged as a potential market. (Carroll & Kincade, 2007)

Problem	*Solution*	*Feature*	*Study*
Difficulty donning and doffing apparel	Use styles that are easy to don and doff	Overhead donning and doffing, side or inseam openings on pants, side front openings, wrap-around styles, snap crotch, side zippers, shoulder opening, envelope neckline, large neck and sleeve openings, two front openings, center back opening, sleeve openings	frescura (1963) schwab & Sindelar (1973) white & Dallas (1977) kernaleguen (1978) reich & Otten (1991)
Difficulty managing fastenings (e.g., hooks and eyes, zippers, buttons) because of restricted use of hands and lack of mobility	Provide easy-to-manage fastenings	Large buttons, large hooks and eyes, flat-rimmed shank buttons, vertical buttonholes, CF zipper/large pull tabs, facing sewn down under zipper, lightweight Velcro dots, no fastenings	behrens (1963) frescura (1963) schwab & Sindelar (1973) reich & Otten (1991)
Lack of freedom of movement for a variety of activities (e.g., crutch walking, wheelchair sitting)	Add features that allow for movement	Action pleats, underarm gusset, box pleats, putting more fabric in the garment, yokes, back hem of jackets raised, elasticized waistlines, scooped-out seat, raglan or kimono sleeves, cut fabric on bias, bigger armscyes	schwab & Sindelar (1973) moran (1976) kernaleguen (1978) reich & Otten (1991)
Inappropriate and uncomfortable fabric	Use fabrics with situational appropriateness	Stretch, smoothness, comfort, ease of care, absorbency, dimensional stability, air circulation, durability, low static, thermal insulation, odor release, hypoallergenic, nonirritant, lightweight, aesthetically pleasing, nonflammable	schwab & Sindelar (1973) warden & Dedmon (1975) reich & Otten (1991)
Inadequate amount of fabric (e.g., body coverage)	Provide extra length	Adjustable hems, extra fabric, overlap skirt panels	behrens (1963) warden & Dedmon (1975)
Not all apparel is aesthetically pleasing	Design apparel with more visual appeal	Attractive styling, color, fashionable	moran (1976)
Styles of apparel can be constricting and uncomfortable, especially during temporary changes	Provide apparel styles that are comfortable and sized appropriately	Big shirts, double waistband, oversized tops and pants, adjustable waistband, maxi dresses, coat-style dress	behrens (1963) frescura (1963) reich & Otten (1991)
Construction quality inadequate for stress exerted by user	Ensure quality, durable construction of all apparel	Reinforcement stitching in stress areas, double stitched seams	kernaleguen (1978)
Inadequate coverage of the body (e.g., for poor circulation)	Ensure coverage in needed areas	High neckline, long sleeves	behrens (1963)
Some features are irritating and get in the way	Adapt features	Sew down collar so it does not ride up on neck, put a pouch pocket on belt	behrens (1963)

Figure 2.13 Summary of design features for physically challenged. Adapted from “Inclusive Design in Apparel Product Development for Working Women With Physical Disabilities” by Carroll, K. E., & Kincade, D. H., *Family and Consumer Sciences Research Journal*, *35*(4), 289–315. 2007, Copyright © 2007 by American Association of Family and Consumer Sciences.

Decades of applied research produced a broad body of work pertaining to design for physically challenged. Carroll and Kincade created a table including explanations of various design solutions features from the apparel literature (Figure 2.13) (Carroll & Kincade, 2007). They also proposed that six universal design principles applicable to apparel product for disabled customers:

1. “equitable use”: users with different abilities can equally wear this garment;

2. “flexibility in use”: the garment can fit to various body shapes;

3. “simple and intuitive use”: the garment can be worn without mistakes;

4. “low physical effort”: the garment is easy for donning and doffing process;

5. “size and space for use”: the garment provides enough space for comfort and mobility.

To address customers’ needs according to Figure 2.13 comfortable and aesthetically appealing garments allowing for sufficient ROM are needed in the market.

CHAPTER 3

METHODOLOGY

The lightweight, multifunctional Dynamic Knee Orthoses System (DKOS) was developed in this study. DKOS was designed 1) to provide support for injured knee joint with lighter physical burden, 2) to restrict range of motion if needed, and 3) to assist regaining range of motion (ROM) in post-surgical rehabilitation process of the knee. The present DKOS is embodied as a pair of close-fitting leggings with a detachable dynamic belt on the waist. Proposed leggings as brace-body interface could lessen physical burden of female users. This chapter demonstrates the orthoses system in detail, in terms of its electro-mechanical design, user configuration and evaluation through human subject tests.

3.1 Electro-Mechanical Design

3.1.1 Leggings with hinges. The leggings described herein include following components (Figure 3.1): (1) hinge (2) fabric to cover hinge (3) straps to fix hinges onto leg (4) leggings.

Figure 3.2 presents the instrumented prototype developed in this study. Two rigid polycentric hinges were placed at both side of legging's right knee area medially and laterally. Rigid hinges provide support to injured knee joint during movement. Polycentric hinges, adopted from a commercial knee brace on the market, have adjustable flexion & extension stops at 90, 60, 30, 15, 0 degrees. The range of motion adjusting panel is located at center of the hinge.

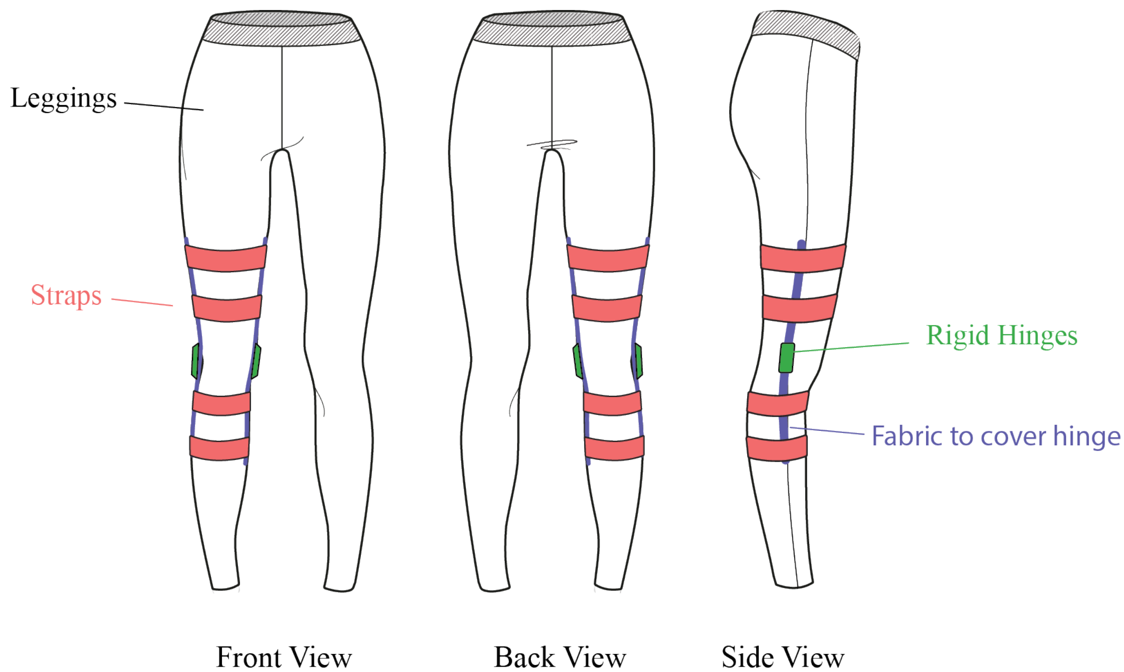
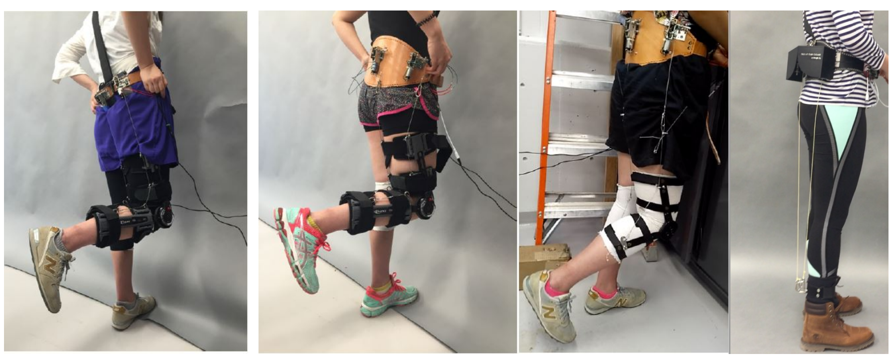


Figure 3.1 Schematic representation of major components

Figure 3.2 Instrumented prototype

Neoprene was used to cover and secure hinges onto legging. Four additional straps (width = 2 inch) with Vecro wrap around leg to provide additional support. Leggings was made at size medium (US size 6-8). Necessity of neoprene and four straps was established during prototyping process. Figure 3.3-d shows one prototype with rigid hinges only. This prototype could not support knee joint since hinge was mounted on highly stretchable fabric.

Hinges interfaced to users through a pair of close-fit leggings. Physical connection between rigid hinges and users kept supportive hinge and knee joint collocated, while provided better thermal and tactile comfort than a commercial knee orthosis.



(a) (b) (c) (d)

Figure 3.3 Prototype process of dynamic knee orthosis system.
a). narrower leather belt with metal cable was used. b). wider belt to improve comfort; c). hinge mounted onto fabric with strap only. d). Kevlar cable replaced metal cable to improve safety; new leather belt with cushion was used to improve comfort.

3.1.2 Dynamic belt system. Dynamic belt was designed to provide accurate control of knee flexion and extension, thus to assist at rehabilitation process. Main components of belt system are shown in Figure 3.4. The developed belt is comprised of off-the-shelf leather belt, two small electric motors, manually operated switch and pre-programmed microcontroller. The prototype was designed to let the users change knee flexion angle according to personal preference or need. The system can be used manually or automatically.

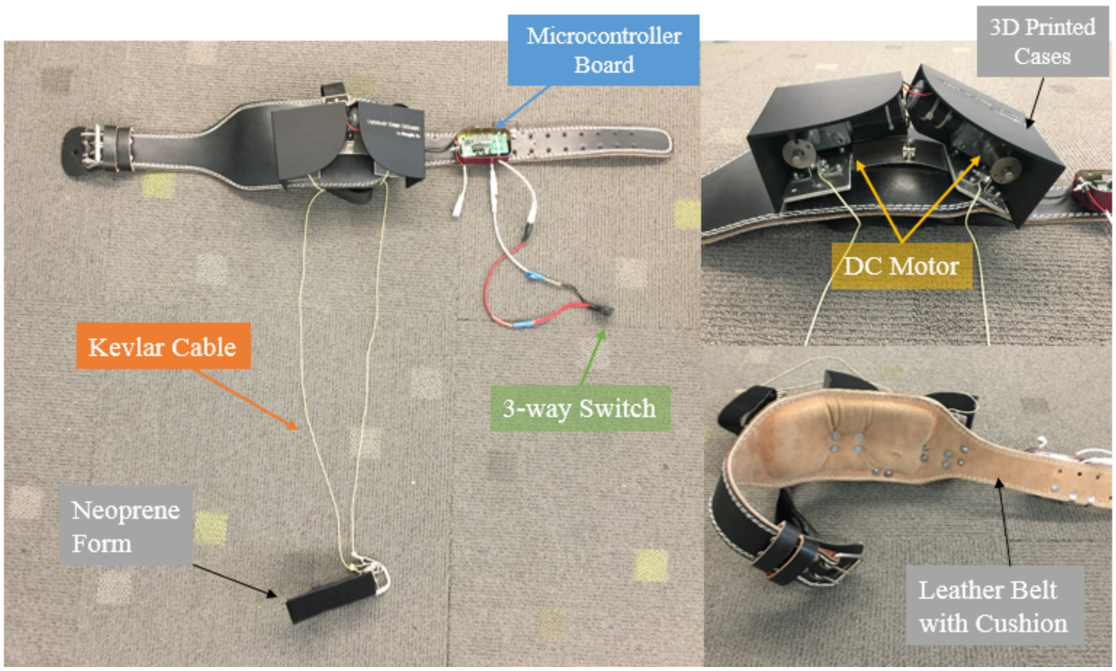


Figure 3.4 Major component of dynamic belt system

The developed belt has multifunctional elements to support the proposed ROM adjusting system. Detailed description are as follows:

1) A leather belt with soft cushions inside was used to attach motors and microcontroller to body;

2) Two DC electro-motors (GW4058-31ZY-290; ChiMing, Shenzhen, China) with 290:1 gear reductions and in planetary gear-heads actuated knee joint motion, a 3d printed case was used to cover both motors;
3) Braided Kevlar cable made of 100% Dupont Kelvar Fiber (500lb, 1.5mm diameter) was used to transfer load from motors to ankles;
4) A 3-way switch to control DC motors manually;
5) A microcontroller board compactible with 12V DC motors was used to send signal to motors and control flexion and extension movement;
6) Neoprene form, acting as a soft cushion between Kevlar cable and ankle joint, was used to attach the system to human foot.

The system uses Kevlar cable with output of motors as illustrated schematically in Figure 3.5. In manual setting, 3-way switch enables user to adjust knee flexion angle according to self-preference or prescription, while microcontroller board mounted on leather belt allows user to regain range of motion automatically. The prototype in this study preset training time (repeated three times) as follows:

1) pause for 3 seconds;
2) flexion for 23 seconds;
3) pause for 3 seconds;
4) extension for 23 seconds.

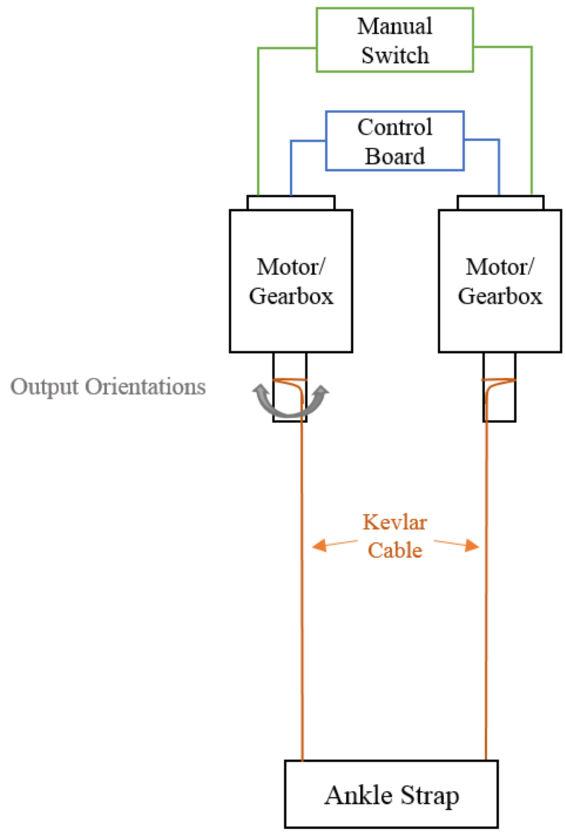


Figure 3.5 Rotary actuator schematic

3.2 User Configuration

This section outlines how to use the developed dynamic knee orthoses system. The prototype was made for females with size medium. Table 3.1 demonstrates size and suggestive body measurement details of this prototype.

Table 3.1

Suggestive body measurement and size for D.K.O.S prototype

U.S. Numeric	Waist (inches/cm)	Hip (inches/cm)
6 R	28/71	38.5/98
8 R	29/74	39.5/100

Proposed donning process for the user is as follows:

1) put on leggings to lower body as usual.

2) place center of two hinges at knee joint level (lateral and medial to the joint line).

3) secure four straps firmly, starting with the two straps closest to the knee.

Presented prototype utilizes two approaches adjusting knee range of motion. D.K.O.S. automatic control system (Figure 3.6) includes actuators and a control board. Manual control makes use of a 3-way switch, enabling users to adjust knee range of motion manually. Figure 3.7 illustrates how to use the belt system.

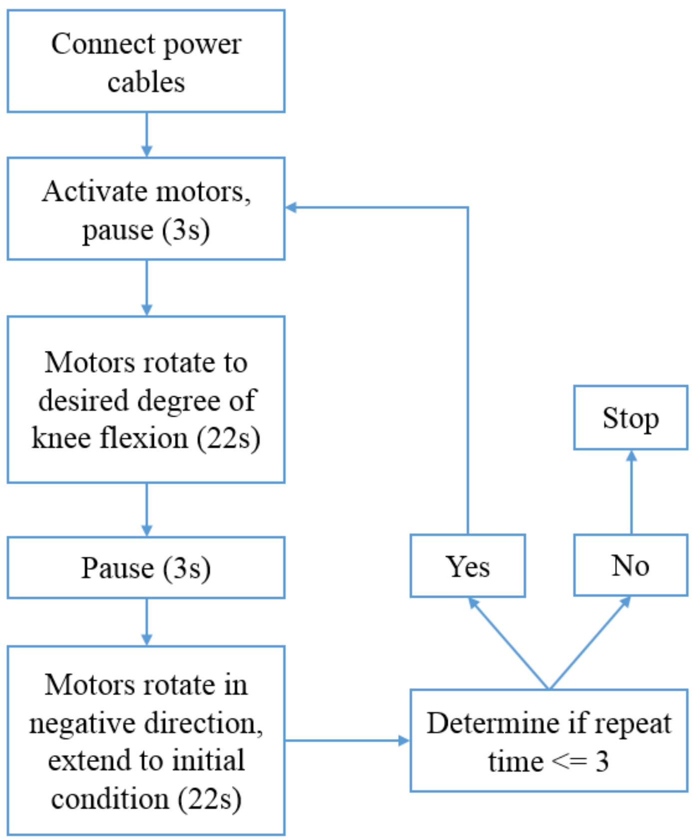


Figure 3.6 Automatic control strategies chart

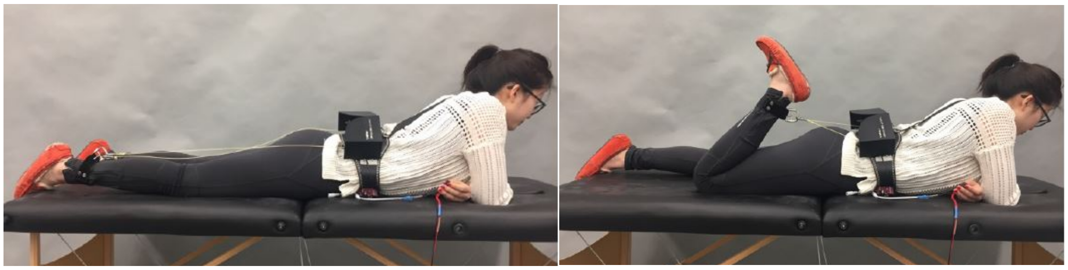


Figure 3.7 User demonstration of dynamic belt system

3.3 Evaluation

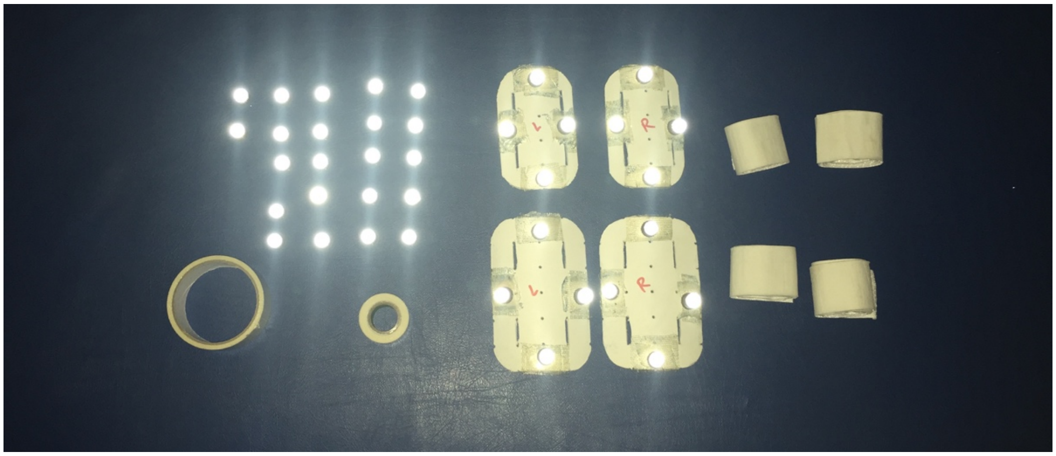
A series of human performance tests were conducted with Institutional Review Board approval at Cornell University and Ithaca College to evaluate effectiveness of the supportive functions by measuring kinematic and kinetic data of lower body and perceived comfort of the developed knee orthosis system by survey. This section specifies the experimental method in detail.

3.3.1 Participants. Ten female uninjured participants with right-leg dominance (average age: 21.5 ± 1.8 years; average height: 169 ± 4.8 cm; average weight: 64.1 ± 6.9 kg) volunteered for the study. Uninjured individuals were recruited to minimize the potential risks that accompany a novel knee orthosis.

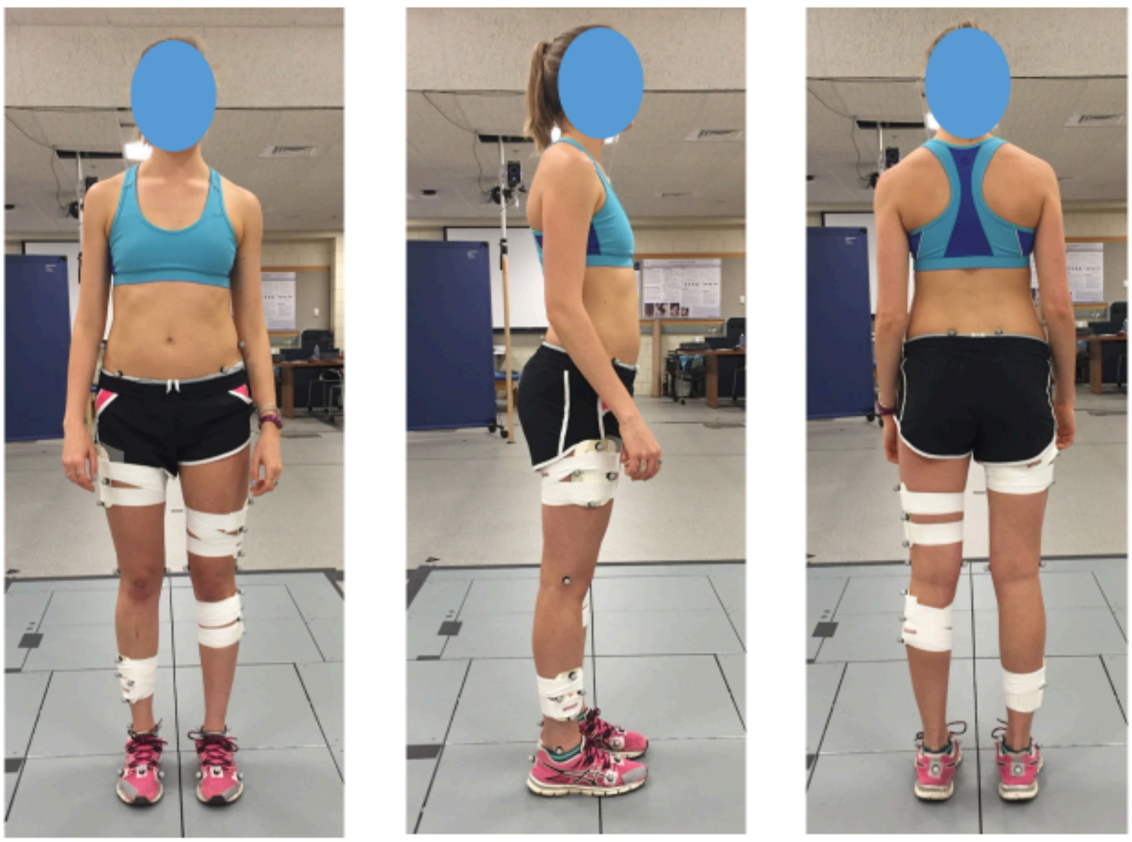
In order to investigate the effect of the orthosis developed in this research on the knee joint, participants wore a control orthosis and the orthosis developed in this research project. Both orthoses were size Medium (requirement of size medium: Waist(cm): 71-74; Hips(cm): 98-100; suggestive U.S. numeric size: 6-8), obtained from suppliers and developed in this research respectively. Therefore, participants of this study were limited to female who fit for available orthosis. All participants were healthy without history of neuromusculoskeletal injuries and any diagnosed issues of gait abnormality. Each subject provided written informed consent. All participants were right-leg dominance to control for a possible effect of dominant leg.

3.3.2 Kinetics and kinematic measurements. The average joint angle of right hip, knee and ankle were calculated. This kinematic data was useful to assess the lower body activity when performing different tasks with different clothing condition. The average joint moment of right hip, knee and ankle were also calculated. By comparing joint angle and moment across different clothing conditions, the supportive effect of the orthosis developed for this study would be evaluated later in data analysis.

Participant's height and weight information were obtained prior to each experiment. 38 Retro-reflective markers were then located on 14 anatomical points on each side of lower body by the same researcher. The reflective markers (14 mm diameter, B&L Engineering, Santa Ana, CA) were attached to participants' skin by a two-sided adhesive medical tape (Figure 3.8). 3-D motion capture system (Vicon®, Culver City, Los Angeles) was used to record the spatial locations of the markers during each test task. Figure 3.9 shows the experiment set up. A force platform consists of four portable force plates (Type 9260AA, Kistler Instrument Corp., Amherst, NY) placed at middle of a level walkway. Ground-reaction forces were measured in three planes (sagittal, frontal and transverse).



(a) Reflective markers set-up before each experiment



Front View　　Side View　　Back View

(b) Reflective markers on one participant

Figure 3.8 Reflective markers

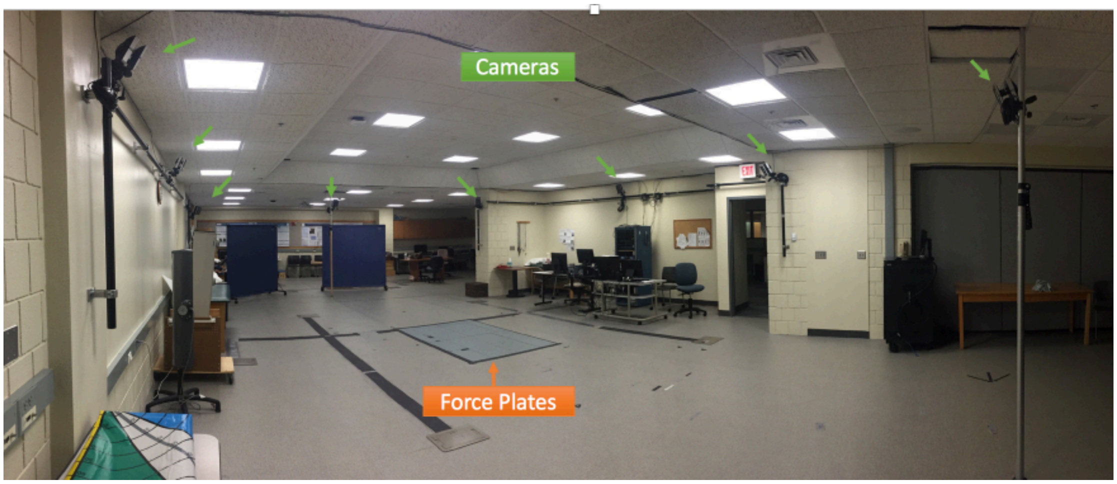


Figure 3.9 Experiment set-up

Each participant performed the following tasks, described below at Table 3.2. after a series of supervised warm up exercise. Tasks were selected based on common clinical tests to assess knee ligament functions (Keays, Bullock-Saxton, & Keays, 2000; Logerstedt et al., 2012; McNitt-Gray, 1993). The test tasks were in an order randomized for different participants. All tasks were demonstrated by the researcher prior to testing and participants practiced tasks to become accustomed to the conditions before experiment. Trials were deemed acceptable if the participant performed the task in a way demonstrated and did not lose their balance. Participant had a rest for approximately 2 minutes between each trial. Three trials of data were collected for each task.

Table 3.2

Task description

Task	Description
Running	Run at a self-selected running speed for 15 seconds. Running speed was monitored throughout the experiment for each participant, to control for the possible effect for speed.
Triple Hop for Distance	Stand on right leg, perform 3 consecutive hop as far as possible and land at the same leg. The trial was deemed successful if the landing was stable with one leg and the participant did not lose balance. (Figure 3.10)
Single Hop for Distance	Stand on right leg, hop as far as possible and land at the same leg. The trial was deemed successful if the landing was stable with one leg and the participant did not lose balance (Logerstedt et al., 2012). (Figure 3.10)
Drop Landing	Step off from a 33.5 cm high wooden platform and land with both feet on the force plate (McNitt-Gray, 1993).

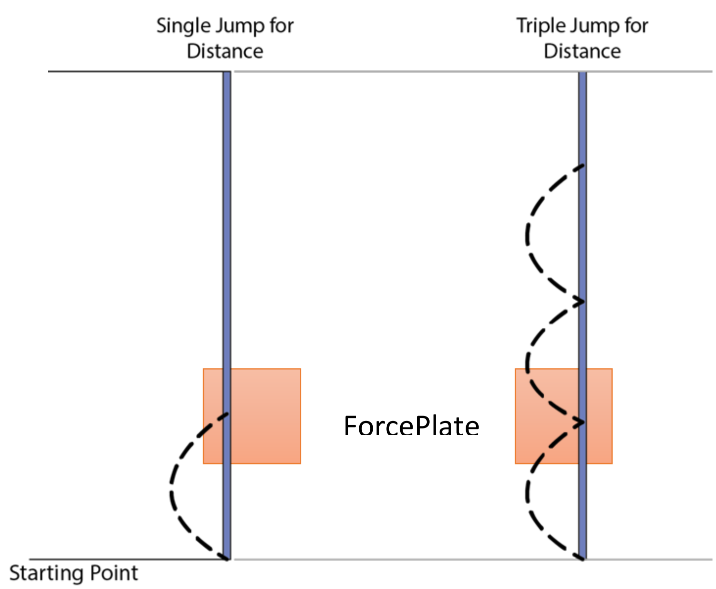


Figure 3.10 Hopping diagram

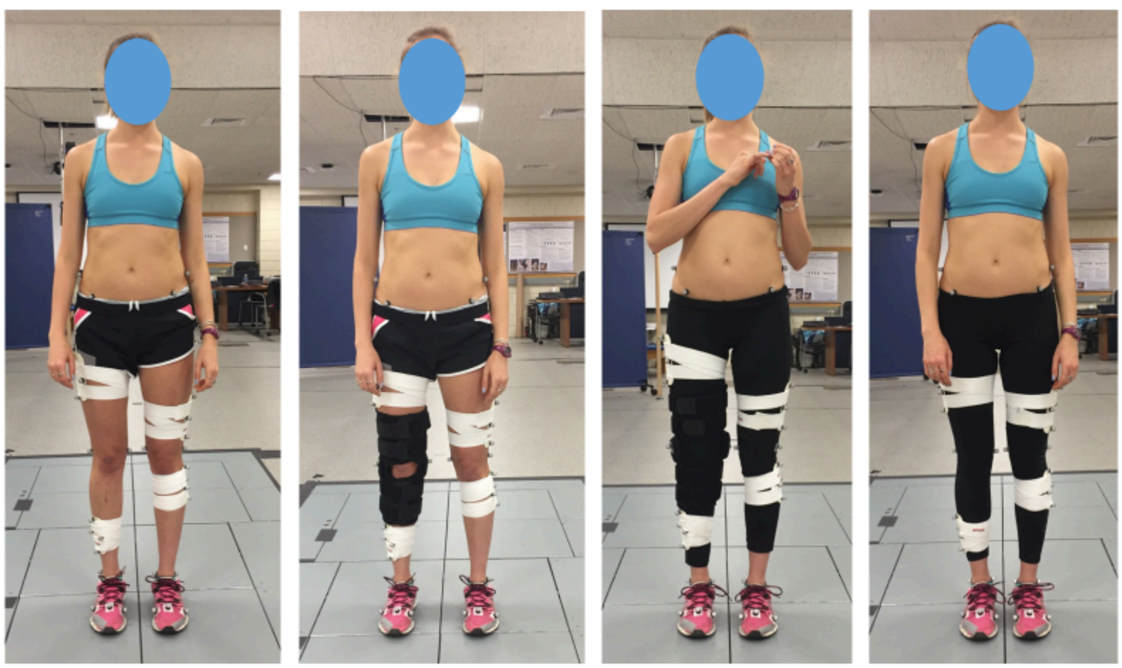
Four clothing conditions are described below (Figure 3.11). The same researcher assisted all the participants with donning and adjusting brace according to the user manual and specifications before each test session. The order of four clothing conditions were randomized for different participant.

1. own running short + no orthosis (Figure 3.11 a);

2. own running short + off-the-shelf orthosis (Gripper (TM) 16" ROM Hinge Knee Brace with Neoprene, Medical Specialities, INC) (Figure 3.11 b);

3. orthosis developed in this research project (Figure 3.11 c);

4. leggings only, made with same materials and same measurements as the leggings developed in this research project (Figure 3.11 d).

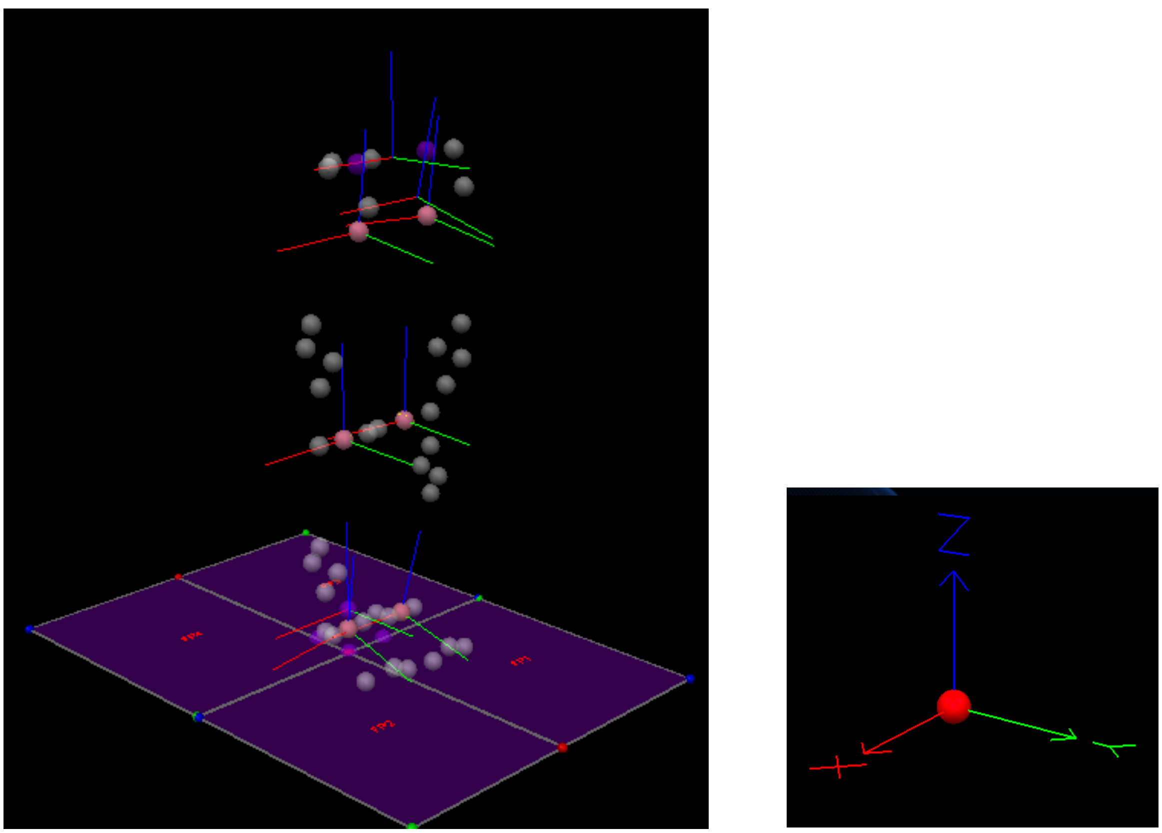


(a) (b) (c) (d)

Figure 3.11 Experiment clothing conditions

Each participant completed all required tasks in all conditions in a day. Any reflective materials on participants' garments and shoes were taped over prior to each test session, to accelerate marker recognition later in data reduction process.

Reflective markers on the subjects' lower body were digitized throughout all the task trials. Figure 3.12 illustrates how markers were digitized and recorded in Cartesian coordinate system. Lower body joint internal moments at each joint were measured using inverse dynamics. The internal moment produced by the muscles was normalized to percentage of body weight. Table 3.3 shows the recording interval for each task.



(a) (b)

Figure 3.12 Digitized markers
a) Digitial representation of lower body of one subject b) Cartesian coordinate system. x-axis, y-axis, z-axis represent flexion/extension, abduction/adduction and internal/external axial rotation respectively

Table 3.3

Kinematic and kinetic data extraction for different tasks

Task	Kinematic and Kinetic Data
Running	From right foot's initial contact (first touch one of the force plate), to terminal stance (right foot leave force plate completely)
Triple Hop for Distance	From right foot's initial contact of first hop (right foot first touch one of the force plate) to the end of propulsion phase of second hop (right foot leave force plate completely).
Single Hop for Distance	From right foot's initial contact (first touch one of the force plate), to 20 frames (1.67 millisecond) after maximum knee flexion
Drop Landing	From right foot's initial contact (first touch one of the force plate), to 20 frames (1.67 millisecond) after maximum knee flexion

3.3.3. Survey Upon the completion of each tasks with clothing condition 2 and 3, the participants completed a survey including 12 survey type questions with a seven-point scale on appearance and comfort (including physical burden, donning and doffing, thermal and tactile comfort) of developed and off-the-shelf orthosis (Figure 3.13). The participants also respond to open-ended questions regarding these two orthoses and the belt as follows:

1) How do you like the idea of this dynamic belt?
2) Would you use this for rehabilitation to regain your range of motion if needed? Why or why not?
3) Do you have any recommendation on the improvement of the developed prototype?

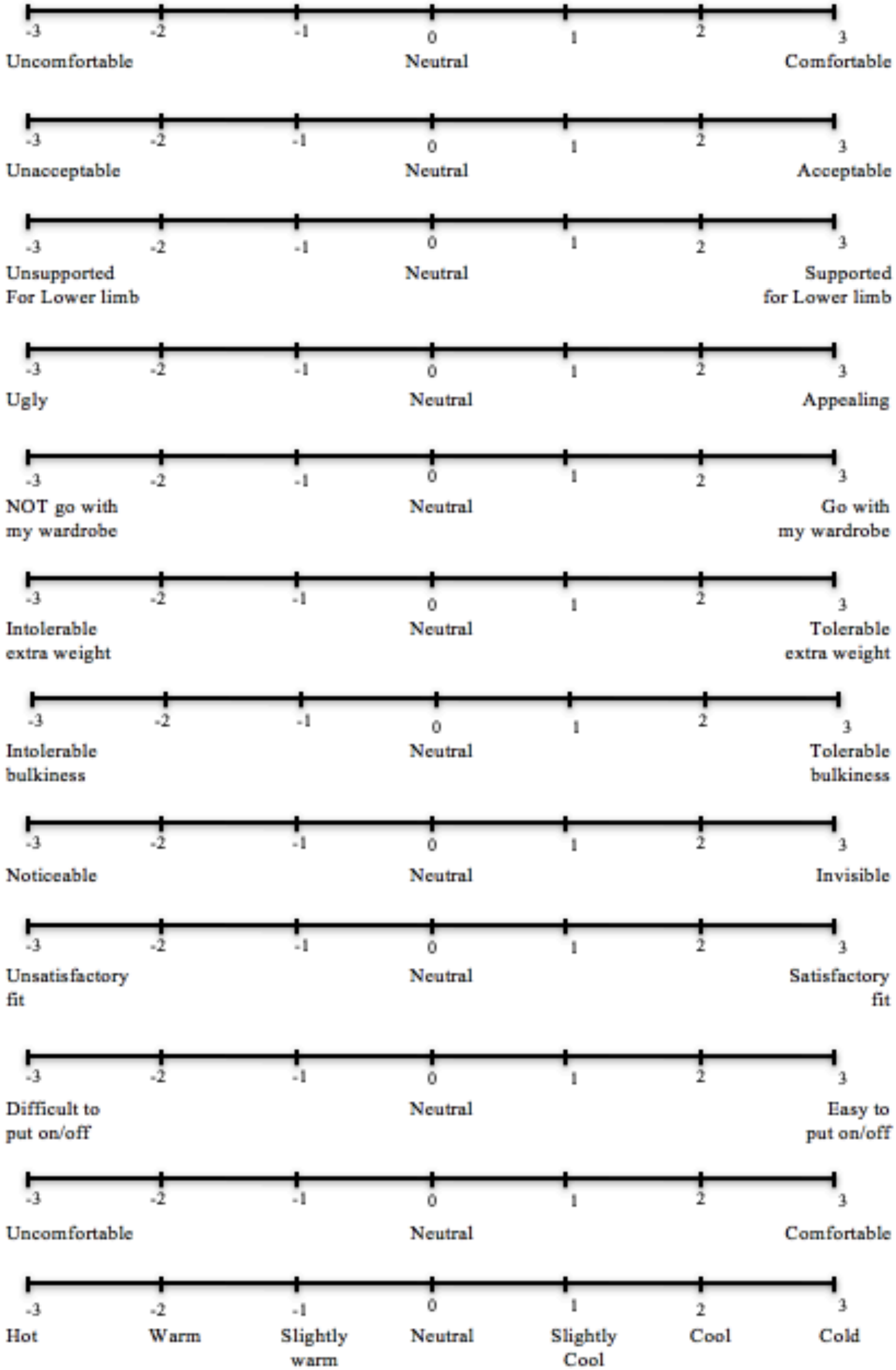


Figure 3.13 Survey questions

3.3.4 Data analysis. Goal of data analysis was to identify the overall trends of joint position and moments of four different tasks and four different clothing conditions in sagittal plane.

This study planned to investigate the anterior-posterior support of two orthoses, since the orthosis mainly provides anterior-posterior support in sagittal plane. Differences in ankle, knee, and hip joint angles and joint moments among different tasks and different clothing conditions reflect the changes in movement and demand of the muscles responsible for flexion and extension to counterbalance the external loads. Flexion moment of hip and knee were hypothesized to be lower for two brace conditions than the control group, since two orthoses absorbs part of external loads during all four tasks.

Kinematic data of hip, knee and ankle joints and ground reaction force with three repeats were recorded for each task and each clothing condition. A total of 480 measurements (ten subjects x four clothing conditions x four tasks x 3 repetitions) were analyzed. Mixed model analysis was employed using RStudio (Version 1.0.143 – © 2009-2016 RStudio, Inc.). The mixed factor analysis was used because of the repeated measurements and multiple garment conditions and multiple tasks. Participants, brace within each participant, and task within each clothing condition were included as nested random effects. The main effects of brace, task, order of both task and brace, and the associated interactions were evaluated. Order of both task and braces were included as fixed effect, so the variability of the difference of orders were taken into consideration. The result of joint position and moments prediction therefore would be more precise.

Least-squares means (LS Means) for the mixed models were employed to estimate and predict the difference of kinetics and kinematics measurements. Post hoc tests using Tukey's pairwise comparisons were conducted. An experiment-wise alpha level of 0.05 was used through all assessments. Effect size was also used to quantify the differences between clothing conditions. Effect size, the standardized mean difference, is the ratio between difference of two group means and the standard deviation of the population. The effect size was corrected for bias using factors proposed by Hedges and Olkin (Hedges'g). The corrected effect size was calculated through "Effect Size Calculators" created by Paul Ellis (Ellis, 2009a). Table 3.4 describes the effect size threshold according to Ellis (Ellis, 2009b).

Table 3.4

Effect size thresholds

Threshold	Standardized mean difference (absolute value)
Small	.20
Medium	.50
Large	.80
Very Large	1.30

3.4 Hypothesis

Four hypotheses about the proposed system are presented as below:

1) The proposed hinged leggings design will enhance movement by increasing average knee joint flexion angles for all tasks, comparing to the commercial brace;

2) The proposed hinged leggings will not have difference in anterior-posterior support for the knee joint, comparing with the commercial brace. The average joint moment of hip and knee joints with the proposed hinge leggings and the commercial brace will not have significant difference for all tasks;
3) Change of interface between hinges and human body will decrease perceived physical burden, including extra weight, bulkiness, thermal discomfort, tactile discomfort and misfit;
4) The proposed dynamic belt system will have positive feedback among participants.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Joint Position and Moment

4.1.1 Joint position. No significant effect on garment conditions were found on joint position. Task order was also found to have a significant effect on knee ($p < 0.001$), hip ($p < 0.01$) and ankle ($p < 0.01$) average position.

Although the difference among garment conditions did not reach a statistically significant level, the data trends suggested that the proposed leggings have positive influence over an increase in knee joint angles for all task.

Average angular kinematic data in running task was recorded during one stance phase of running (from heel strike to toe off). As shown in Table 4.1 and Figure 4.1, 4.2, when running with a commercial brace (C2), the participants had 23% less flexion than control group (C1: No brace). Yet the difference of angular kinematics of hip between the hinged leggings (C3) and control group (C1: No brace) is barely noticeable (0.2%). It had an effect size of 0 (SE = 0.45). While wearing a pair of regular leggings (C4), the participants had 40.5% less hip flexion than control group. The difference has an effect size of -0.43 (SE = 0.45). As described at Table 4.1 and Figure 4.2, C3 and C4 had similar garment effect on average position of knee and ankle, comparing to control group. Participants generally had similar knee flexion (effect size = -0.12, 0.1 respectively) and more ankle dorsiflexion (effect size = -0.66, -0.66 respectively). While

Table 4.1

Least squares mean (LS Mean), Standard error (SE), effect size and standard error (SE) for average joint position (degree)

Garment Condition	Running			Single Hop			Triple Hop			Drop Landing		
	Hip	Knee	Ankle	Hip	Knee	Ankle	Hip	Knee	Ankle	Hip	Knee	Ankle
C1												
LS Mean	6.90	-28.49	-2.60	35.99	-39.55	-7.20	16.78	-33.71	-1.60	36.90	-55.78	5.80
SE	3.57	4.22	2.02	3.56	4.22	2.02	3.62	4.29	2.04	3.55	4.21	2.01
C2												
LS Mean	5.30	-23.78	-2.00	35.73	-41.34	-3.20	18.65	-33.99	-0.30	38.71	-50.87	7.20
SE	3.57	4.22	2.02	3.56	4.22	2.02	3.61	4.27	2.03	3.55	4.21	2.01
C3												
LS Mean	6.92	-29.43	-5.00	36.75	-42.06	-7.50	19.05	-36.40	-1.60	36.73	-61.60	6.00
SE	3.57	4.22	2.01	3.59	4.25	2.02	3.66	4.31	2.04	3.56	4.22	2.01
C4												
LS Mean	4.10	-27.69	-5.00	32.44	-43.18	-8.30	13.47	-34.34	-2.80	33.71	-60.48	4.90
SE	3.58	4.24	2.03	3.58	4.24	2.03	3.63	4.29	2.05	3.57	4.23	2.03
C1 - C2												
Effect Size	-0.25	0.62	0.16	-0.04	-0.23	1.10	0.29	-0.04	0.35	0.28	0.64	0.38
SE	0.45	0.46	0.45	0.45	0.45	0.48	0.45	0.45	0.45	0.45	0.46	0.45
C1 - C3												
Effect Size	0.00	-0.12	-0.66	0.12	-0.33	-0.08	0.35	-0.35	0.00	-0.50	-0.76	0.05
SE	0.45	0.45	0.46	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.46	0.45
C1 - C4												
Effect Size	-0.43	0.10	-0.66	-0.55	-0.47	-0.30	-0.51	-0.08	-0.33	-0.03	-0.62	-0.25
SE	0.45	0.45	0.46	0.46	0.45	0.45	0.45	0.45	0.45	0.45	0.46	0.45

Note. C1: No brace (control group) C2: Commercial Brace C3: Developed Leggings C4: Leggings only

Hip: Positive sign stands for flexion and negative sign stands for extension;

Knee: Positive sign stands for extension and negative sign stands for flexion;

Ankle: Positive sign stands for dorsiflexion and negative sign stands for plantarflexion.

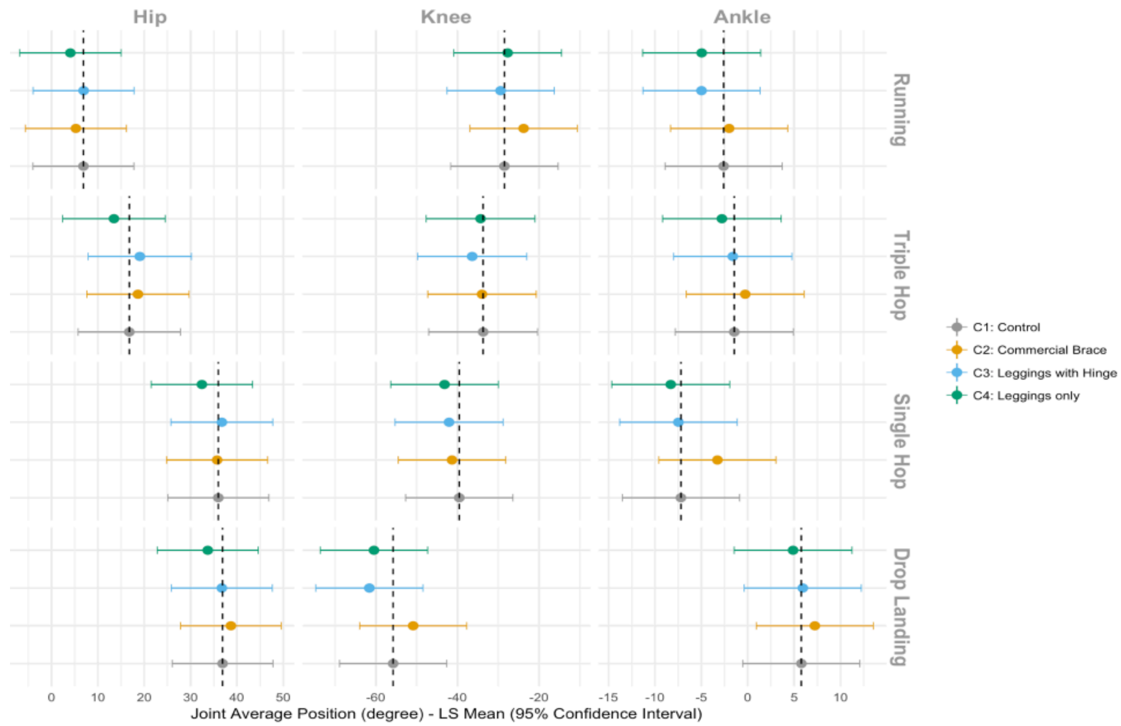


Figure 4.1. Joint average position for four clothing conditions across four tasks. Dotted line in color gray represents the respective value of control group. Hip: Positive sign stands for flexion and negative sign stands for extension; Knee: Positive sign stands for extension and negative sign stands for flexion; Ankle: Positive sign stands for dorsiflexion and negative sign stands for plantarflexion.

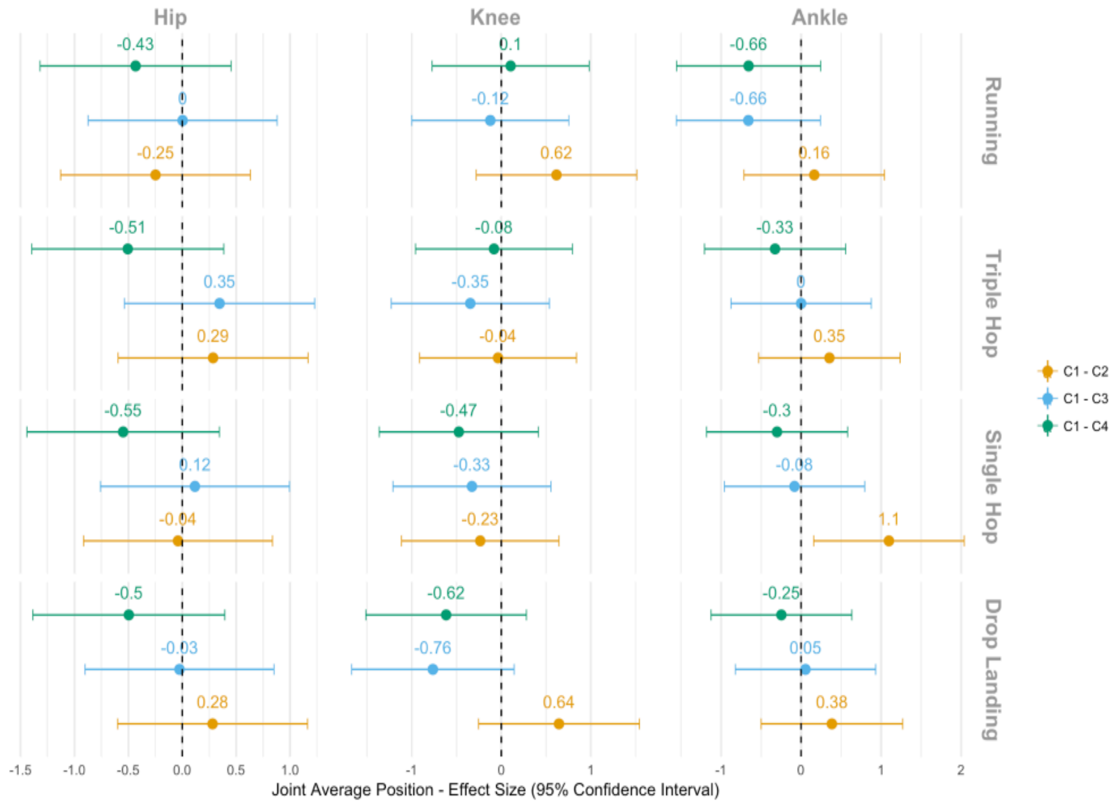


Figure 4.2. Effect size for joint average position for four clothing conditions across four tasks. Dotted line in color gray represents value zero. Hip: Positive sign stands for less flexion and negative sign stands for more flexion than C1; Knee: Positive sign stands for more extension and negative sign stands for more flexion; Ankle: Positive sign stands for more dorsiflexion and negative sign stands for more plantarflexion. C1: No brace (control group); C2: Commercial Brace; C3: Developed Leggings; C4: Leggings only

wearing C2, the participants had 16.5% less knee flexion and 23.1 less dorsiflexion during running, and compared to control group (C1). Participants had similar hip and knee flexion angle wearing proposed hinged leggings (C3) compared to control condition. Commercial brace(C2) limited both hip and knee flexion during stance phase of running. The proposed hinged leggings (C3), on the other hand, did not restricted movement during running.

Triple hop task data recorded the landing of first jump and the propulsion phase of second jump. As shown in Table 4.1 and Figure 4.1, 4.2, with C2, participants had 11.2% more hip flexion, 0.8% more knee flexion and 81.2% more ankle plantarflexion. The magnitude of difference between C1 and C2 was relatively large regarding hip and ankle average position (effect size = 0.29, 0.35 respectively) than knee joint (0.04). With C3 however, the magnitude of difference between C1 and C3 was relatively large on hip and knee (effect size = 0.35, -0.35 respectively), comparing to the ankle difference (effect size = 0). Proposed legging design increased knee and hip flexion angle compared to the control group. Commercial brace on the other hand, restricted ankle plantarflexion during triple hop task and seemed to have no effect on knee flexion angle. The results showed that participants wearing proposed leggings (C3) could recruit muscles on the lower body and can generate more motions in sagittal plane during triple hop.

In single-leg hop for distance task, average angular kinematic data was recorded from initial contact on force plate to 20 frames (1.67 millisecond) after peak knee flexion angle occurred. Therefore, the joint position data were different than triple hop. According to Table 4.1, and Figure 4.1, 4.2, two brace conditions (C2 and C3) had similar garment effect on hip average position (effect size = -0.04 and 0.12 respectively). While the difference between C4 and control group was comparably larger. It had effect size of -0.55 (SE 0.46). As for knee average position, all three clothing conditions had relatively small difference (-0.23, -0.33, -0.47 respectively). Participants tended to have more knee flexion during single hop landing (4.5%, 6.3%, 6.6% respectively). As for ankle average position, two legging conditions had similar garment effect (effect size =

-0.06, -0.3 respectively). Yet participant wearing the commercial brace (C2) had 15.2% less dorsiflexion than wearing control group. Participants had similar knee and hip flexion during single hop landing with C2 and C3. Both brace conditions helped enhance knee flexion. While commercial brace (C2) restricted ankle plantarflexion movement.

Kinematic data for drop landing task was recorded similarly to single hop. Joint position from initial contact on force plate to the time when peak knee flexion angle occurred was captured and calculated. The sample results from Table 4.1 showed 0.5% less hip flexion (effect size = -0.5), 10.4% more knee flexion (effect size = -0.76), and 3.4 % less ankle plantarflexion (effect size =0.05) while drop landing with C3, comparing to control group. While drop landing with C2, participants had more flexion on hip (4.9%, effect size = 0.28), less flexion on knee (8.8%, effect size =0.64) and more plantarflexion on ankle (3.4%, effect size = 0.05). These result showed that participants tended to have more erect style with extended joints during drop landing with C2, while more engaged position with C3.

Overall data trend suggested that proposed hinged legging design (C3) increased knee joint flexion angles during four different tasks, while the commercial brace (C2) restricted movement at knee joint. Since the proposed legging design kept straps and hinges only, participant seemed to have more freedom in movement without the neoprene cover of the commercial brace. These results indicated patient wearing the proposed leggings (C3) would have less potential muscle atrophy. C4 (leggings only) generally had different effect than control group and C3. Participants with C4 had less hip flexion (Running: effect size = -0.43, triple hop: effect size = -0.51, single hop:

effect size = -0.55, drop landing: effect size = -0.5). Participants with C4 had similar knee flexion ankle during running and triple hop tasks (effect size = 0.1, -0.08, respectively), while less knee flexions during single hop and drop landing tasks (effect size = 0.-47, -0.62, respectively). Such differences suggest that hinge and straps had more positive effect on knee joint angles than legging materials.

4.1.2 Joint moment. No significant effect on garment conditions were found on joint moment in the proposed mixed model. There is no significant effect on task and garment order as well.

Although the difference among garment conditions did not reach a statistically significant level, the data trends suggested that the lower extremity joint moment of right limb was in contradiction to hypothesis 2. The kinetics of right limb were affected by the different knee brace conditions (Table 4.2, Figure 4.3, 4.4). Yet different garment effects were observed between proposed legging and the commercial brace.

Running task record the stance phase of one running gait cycle. The extensor moment at hip was slightly increased while running with C3 and C4 (effect size = -0.28, -0.48 respectively) than control group. Trivial difference (effect size = -0.06) on hip moment was observed between C2 and control group (C1). All three conditions had smaller flexion moment on knee than the control group (C1). A relatively large difference (effect = 1.21, decrease by 21.8%) on knee moment appeared between C2 and control group. While other two conditions had relatively small to trivial difference

Table 4.2

*Least squares mean (LS Mean), standard error (SE), effect size and standard error (SE) for average joint moment (N*m/kg)*

Garment Condition	Running			Single Hop			Triple Hop			Drop Landing		
	Hip	Knee	Ankle	Hip	Knee	Ankle	Hip	Knee	Ankle	Hip	Knee	Ankle
C1												
LS Mean	-7.68	-76.72	83.71	72.61	-88.67	58.37	50.55	-80.48	87.27	33.52	-76.62	53.60
SE	9.14	7.65	4.96	9.13	7.65	4.96	9.23	7.74	5.05	9.12	7.63	4.94
C2												
LS Mean	-8.69	-59.98	77.24	70.88	-94.67	54.68	51.47	-68.23	91.67	34.16	-63.55	52.20
SE	9.14	7.65	4.96	9.13	7.65	4.96	9.21	7.72	5.02	9.12	7.63	4.94
C3												
LS Mean	-24.69	-75.48	81.42	63.39	-96.18	51.50	44.66	-78.21	84.04	30.00	-74.77	52.46
SE	9.13	7.64	4.96	9.18	7.68	4.99	9.28	7.77	5.08	9.13	7.64	4.95
C4												
LS Mean	-15.69	-70.00	85.02	54.34	-95.00	52.46	32.18	-80.62	89.33	27.46	-77.25	52.03
SE	9.17	7.72	4.98	9.17	7.72	4.98	9.24	7.79	5.04	9.15	7.71	4.96
C1 - C2												
Effect Size	-0.06	1.21	-0.72	-0.11	-0.43	-0.41	0.06	0.88	0.48	0.04	0.95	-0.16
SE	0.45	0.49	0.46	0.45	0.45	0.45	0.45	0.47	0.45	0.45	0.47	0.45
C1 - C3												
Effect Size	-0.28	0.09	-0.26	-0.56	-0.54	-0.76	-0.35	0.16	-0.35	-0.21	0.13	-0.13
SE	0.45	0.45	0.45	0.46	0.46	0.46	0.45	0.45	0.45	0.45	0.45	0.45
C1 - C4												
Effect Size	-0.48	0.48	0.15	-1.10	-0.46	-0.66	-1.10	-0.01	0.23	-0.37	-0.05	-0.17
SE	0.45	0.45	0.45	0.48	0.45	0.46	0.48	0.45	0.45	0.45	0.45	0.45

Note. C1: No brace (control group) C2: Commercial Brace C3: Developed Leggings C4: Leggings only

Hip: Positive sign stands for flexion and negative sign stands for extension;

Knee: Positive sign stands for extension and negative sign stands for flexion;

Ankle: Positive sign stands for dorsiflexion and negative sign stands for plantarflexion.

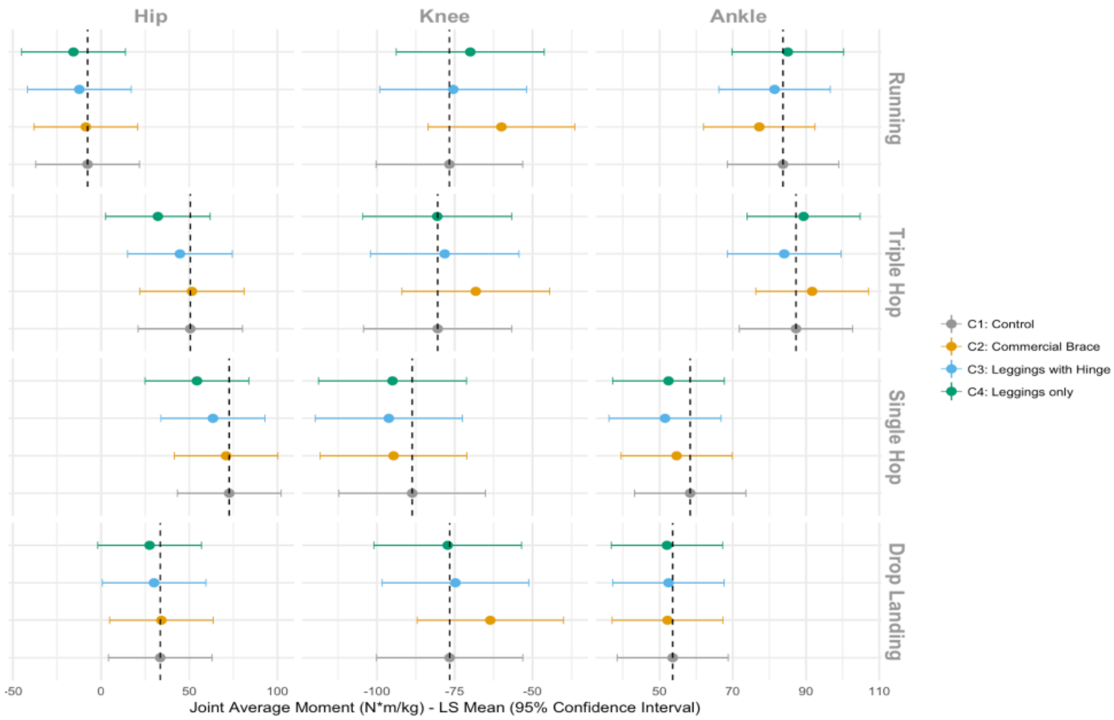


Figure 4.3. Joint average moment for four clothing conditions across four tasks. Dotted line in color gray represents the respective value of control group. Hip: Positive sign stands for flexion and negative sign stands for extension; Knee: Positive sign stands for extension and negative sign stands for flexion; Ankle: Positive sign stands for dorsiflexion and negative sign stands for plantarflexion.

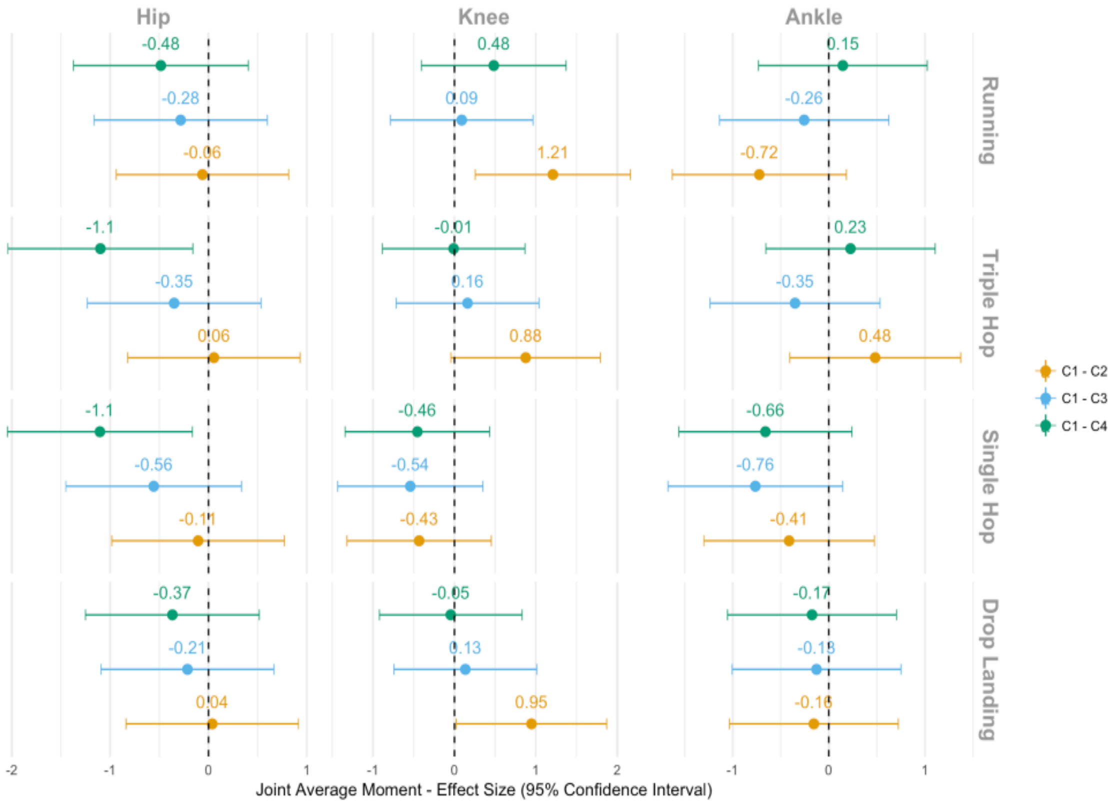


Figure 4.4. Joint average moment for four clothing conditions across four tasks. Dotted line in color gray represents value zero. Hip: Positive sign stands for less flexion and negative sign stands for more flexion than C1; Knee: Positive sign stands for more extension and negative sign stands for more flexion; Ankle: Positive sign stands for more dorsiflexion and negative sign stands for more plantarflexion. C1: No brace (control group) C2: Commercial Brace C3: Developed Leggings C4: Leggings only

(C3: decreased by 1.6%, effect size = 0.09; C4: decreased by 8.8%, effect size = 0.48). Both C2 and C3 had less plantarflexion moment at ankle than control group. The magnitude of difference is larger at C2 than C3. (C2: decreased by 13.7% effect size = -0.72; C3: 2.7% effect size = -0.26). There is trivial difference on ankle plantarflexion moment between C4 and control group (effect size = 0.15). The decreased moment at knee while running with C2 indicated smaller quadriceps muscle force, therefore, smaller strain and force at knee ligament. The proposed legging on the other hand, did not reduce knee moment during running, possibly since C3 did not restrict leg movement. The results showed that C3 may not have similar protective effect as the commercial brace during running.

Kinetics data during triple hop task were recorded from landing of first jump and propulsion phase of second jump. Participants with both legging conditions had smaller flexion moment on hip than with the control group. A relatively large difference (effect = -1.1, decrease by 36.3%) on hip flexion moment appeared between C4 and control group. While C3 had relatively small difference (decreased by 11.7%, effect size = -0.36). C4 slightly increased hip average flexion moment by 1.8% (effect size = -0.05) and the difference is trivial. Two legging conditions (C3 and C4) had similar garment effect on knee average moment (effect size = 0.16 and -0.01 respectively). While the difference between C2 and control group was comparably larger. It had effect size of 0.88 (15.2% decreased knee flexion moment, SE = 0.47). As for ankle average moment, participant had 5% less plantarflexion moment wearing C3, more plantarflexion moment wearing C2 and C3 (5% and 3.7% respectively). The effect sizes of the ankle joint were considered small (C2: 0.48, C3: -0.35, C4: 0.23). Like the running task, the commercial brace (C2) seemed to have a protective effect on knee ligament because of the decreased knee moment. Proposed legging (C3) did not have such garment effect.

Single hop tasks record joint moment during landing phase (from initial contact on the force plates to 20 frames (1.67 millisecond) after peak knee flexion angle occurred). Compare to the control group, participants with C3 and C4 had decreased flexion moment at hip. The magnitude of change with C4 was larger than C3 (effect size = -1.1, -0.56 respectively). There was trivial difference between C2 and control group (effect size = -0.1). Difference of average knee and ankle moment were relatively consistent among C2, C3 and C4. Participants with all three condition had increased knee flexion moment (effect size = -0.43, -0.54 and -0.46) and decreased ankle plantarflexion moment (effect size = -0.41, -0.76 and -0.66). Participant with both commercial brace and proposed hinged leggings had increased knee moment during single hop. Similar garment effect suggested that participant recruited more quadriceps muscles during single hop. Extra weight of both C2 and C3 on right knee may be the reason for more quadriceps muscle force. The decreased hip moment with C3 indicated a possible less hamstring muscle force.

Average joint moment data during drop landing task were recorded from initial contact on the force plates to the time when peak knee flexion angle occurred. Difference of moment at both hip and ankle were relatively consistent across C2, C3 and C4 for drop landing task. Both legging conditions had small difference (-0.21, -0.37 respectively) on average hip moment while C2 had trivial difference (effect size = 0.04) between control group. All three conditions had trivial difference on average ankle moment (-0.16, -0.13 and -0.17). C2 and control group had a relatively large difference on average knee moment (0.95). Participant with C2 had 17.1 % less knee flexion moment during drop landing than control group. Yet C3, C4 had trivial difference on knee moment comparing to control group. Data trend observed here was like running and triple hop task. The proposed design did not have similar garment effect as the commercial brace. Participant with the hinged leggings had similar knee moment as control group.

Different garment conditions changed the joint position and moments during different tasks. The proposed legging (C3) had similar effect on joint moment as control group (C1) except single hop task. These results suggest that commercial brace (C2) may protect injured knee ligament during running, triple hop and drop landing task, while the proposed leggings may not have such supportive function. Discrepancy between single hop and triple hop data trend was observed. Such difference indicates that the proposed legging may not have effect on taking-off phase of single-leg hop, yet have similar effect on landing as the commercial brace.

Although the supportive benefit of knee brace had not been scientifically verified, the proposed hinged leggings (C3) seemed to fail to enhance the stability of an unstable knee. Given the result that proposed hinged legging (C3) improved range of motion yet did not lessen extra anterior-posterior strain at knee ligament, this design may be suitable for healing phase of knee injury, and may not to be used right after acute knee injury or surgery.

4.2 Subjective Assessment

4.2.1 Leggings with hinges. Overall, participants reported more positive feedback regarding the developed orthosis (C3), comparing to the commercial brace (C2). These results support hypothesis three. Change of interface between hinges and human body would decrease perceived physical burden, including extra weight, bulkiness, thermal discomfort, tactile discomfort and misfit. As shown in Figure 4.5, the mean overall comfort, overall acceptability, and overall support had considerably higher rating than the commercial brace (1.5 vs -0.15, 1.4 vs 0.75, 1.45 vs 1.3 respectively). All 10 participants liked the proposed brace (C3) better, with better experience regarding appearance, physical burden, fitting, donning and doffing process, tactile and thermal comfort.

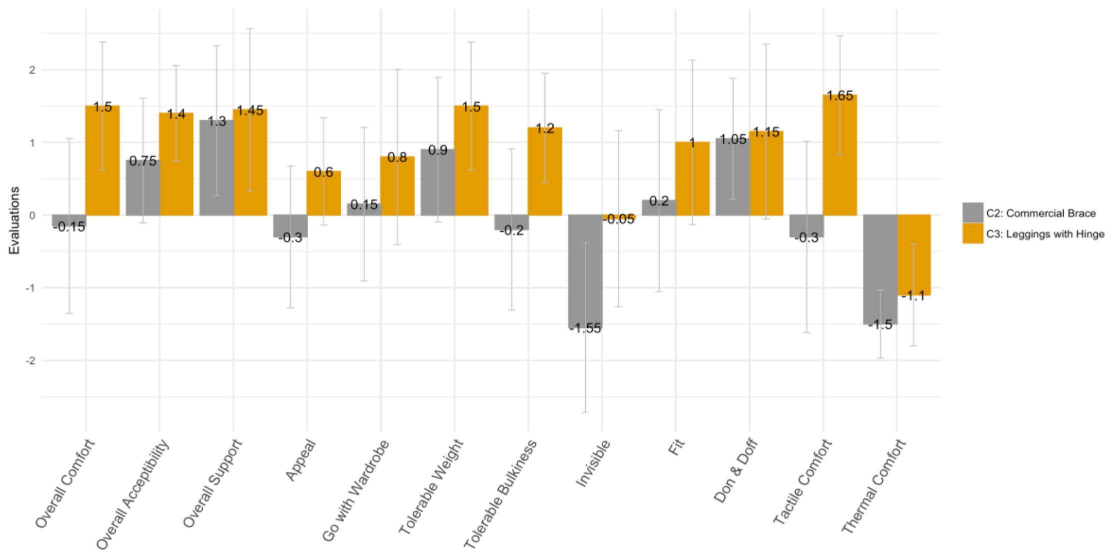


Figure 4.5 Subjective evaluation of two braces

In comparison with the commercial brace, the proposed brace improved appearance rating from -0.3 (SD = 0.74) to 0.6 (SD = 0.98) in "Appeal" and 0.15 (SD = 1.21) to 0.8 (SD = 1.06) regarding "Go with Wardrobe". Weight of both braces was perceived as tolerable. Some participant mentioned the main area they felt the extra weight for the commercial brace is "upper front knee". Proposed brace had 66% better result than the commercial brace. Bulkiness of proposed brace was perceived as tolerable (1.2, SD = 0.75), whereas the commercial brace was generally considered as "intolerable" (-0.2, SD = 1.11). One participant complained that she felt "bulky and heavy everywhere the (commercial) brace is". Both braces were perceived as not invisible. The proposed brace was reported less visible (-0.05, SD = 1.21) than the commercial brace (-1.55, SD = 1.17).

Participants had similar donning and doffing experience for both braces. One participants mentioned that the strap design on both braces made donning and doffing a less satisfying experience. Another participant said hinges on leggings was the main obstacle for doffing process. She mentioned that "putting on (the legging) was fine, but taking off on right leg was difficult because of the hinges". Since hinges was essential at brace design, the result was not surprising.

The commercial brace was considered as less satisfactory fit (0.2, SD = 1.25) than the proposed brace (1, SD= 1.13). 4 out of 10 participants reported "sliding off" was the main issue of the commercial brace. Other comments regarding the commercial brace were "loose above right knee" and "lack of stretch when knee goes into flexion". The main fitting issues of the proposed brace was "waist drop". Proposed legging design improved the interface between hinges and body by attaching both hinges at leggings.

The proposed brace had very positive tactile comfort feedback (1.65, SD =0.82) than the commercial brace (-0.3, SD = 1.32). Negative feedback of commercial brace included "itchy upper and lower edges", "upper edge/edges at back and upper front knee rubbing (the skin)", "the Velcro tape (touching the skin) is pretty uncomfortable".

Participants felt "slightly warm" or "warm" for both braces, with proposed brace slightly cooler than the commercial brace (-1.1, SD =0.70, -1.5, SD =0.47 respectively). Area of warm sensation came from "the back of the knee", "upper and lower edges of commercial brace”, “upper front thigh of commercial brace”, “medial knee” and “legging material”. Neoprene material of the commercial brace increased warmth, excessively compressed muscle and irritate skin around knee area. Without the neoprene, the proposed leggings improved tactile comfort and thermal comfort experience during different task.

In summary, the proposed leggings (C3) improved the psychologic aspect of the bracing experience, which is the primary reason of prescribing knee brace clinically (Cawley, France, & Paulos, 1991b; Martin, 2001). The improved interface between hinges and body provided better thermal and tactile comfort, reduced slippage and better fit. According to Cawley et al, some patients after knee injury were dependent upon knee braces due to psychologic reasons (Cawley et al., 1991b). The proposed legging can be used to help improve confidence of patients at rehabilitation exercise program, daily life and sports activities, with more comfort and no inhibition of athletic performance.

4.2.2 Dynamic belt system. Subjective evaluation of the dynamic belt system agreed with hypothesis 4. Nine out of ten participants would want to use the dynamic belt system for knee rehabilitation. Positive feedback included “patient in control of the whole flexion process”, “easy to use”, “easy to put on”, “good way to do rehabilitation on your own”, “consistent result”, “It could be incorporated into home exercise program to regain ROM after surgery. It could cut back on the time spend doing ROM in Physical Therapy sessions. PT sessions could focus on other rehab strategies so that the patient could benefit for longer treatment”. Concerns and suggestions of the system included “sizing”, “speed control”, “used in lying down position only, hip might be compensating and decrease knee flexion angle”, “need someone’s help to strap ankle”, “no extension function” and “need further consideration for special population (overweight and senior for example)”.

CHAPTER 5

CONCLUSION

The present work provided a lightweight and aesthetically more acceptable orthosis alternative, with a dynamic belt system to help with knee ROM rehabilitation. This investigation examined both objective and subjective aspect of brace usage, as suggested by Kramer et al (Kramer, Dubowitz, Fowler, Schachter, & Birmingham, 1997b).

Objective performance test intended to find out that if proposed leggings with hinges (C3) had similar effect as commercially available brace by comparing with "no brace" condition. "Quadriceps avoidance gait" was observed with participants with a commercial brace (C2). Participant tended to be more erect and had less flexion angle at knee joints during running (16.5%) and drop landing (8.8%) tasks while wearing a commercial brace. They tended to have less knee flexion moment during running, triple hop and drop landing (21.8%, 15.2% and 17.1% respectively). "Quadriceps avoidance gait" usually occurred in people with ACL-deficient knees and has negative impact on shock absorption. "Quadriceps avoidance gait" usually associated with decreased quadriceps muscle functions and accelerate degenerative changes at knee joints (Snyder-Mackler, Delitto, Bailey, & Stralka, 1995). Less knee flexion during landing would decrease the shock absorption thus excessive external load from ground reaction force would occur. It is likely to increase risk of potential injury. The proposed leggings (C3), however, did not have such negative effect on participant as evidenced by the effect size between C3 and C1 during running, triple hop and drop landing (effect size

= 0.09, 0.16, 0.13 respectively). A possible reason is that flexible materials of the leggings had no constraint on quadriceps muscles.

Although proposed leggings with hinges did not restrict knee flexion angle, flexion of the femur increases the anterior translational strain on ACL (Levangie & Norkin, 2011). A knee brace is considered as supportive for the knee joint if it reduces strain and forces at the knee ligaments. The findings of this study show that the proposed leggings with hinges is less supportive than the commercial brace during running, triple hop and landing and possibly supportive at single hop task. Hypothesis two was not supported. The proposed leggings, therefore, can be used for later phase of rehabilitation when the focus is muscle strengthening. The proposed leggings can also be used for initial healing period of acute injury (ACL, PCL, LCL, MCL, or meniscus) or surgery (France & Paulos, 1994), to control knee flexion/extension angles.

The result from subjective evaluation shows that participant felt the proposed leggings was more comfortable yet had same support as commercial brace. The proposed leggings had noticeable higher satisfaction on perceived physical burden, so the appearance, wardrobe compatibility, perceived weight, bulkiness, invisibility, fit, and donning/doffing process was improved. The commercial brace also performed poorly in terms of perceived thermal and tactile comfort. One participant reported that "I can feel the moisture after doffing. Temperature rose a lot after any a few mins of activities". The proposed leggings eliminate neoprene materials of the commercial brace, thus provide a better interface between human body and the hinges in terms of tactile, thermal comfort, fit and bulkiness.

As for the dynamic belt system, participants liked the innovative idea of automatic and manual control system. With flexibility of control options, patients undergo knee rehabilitation program could independently regain range of motion. However, the dynamic belt system could be used in prone position only. Future design endeavors could explore design ideas for more versatile positions.

This study served as a basis for future investigation on effect of knee bracing. There are several limitations of this research. Firstly, due to relatively small (10 healthy participant in total) sample size of the biomechanical evaluation, the findings of this investigation should be used and generalized with caution. Secondly, this study recruited healthy participants. People with knee injuries may have different responses to test knee braces. The population of people with knee injury have large variation on treatment, rehabilitation protocols, compliance with rehabilitation and activity levels. Variation need to be controlled during future test. Future research can focus on evaluation on injured population and ligament specific effect. Thirdly, although four tasks (running, single hop, triple hop and drop landing) were given to participant in randomized order and participants had rest between each trial, order of task still appeared to be statistically significant at joint position measurement. Future study should consider experiment protocols balanced for the residual effects of task order. It is also worth mentioning that this study only evaluated the joint position and moment in sagittal plane. Future investigation of all three planes movement can add more meaningful information to the study. Moreover, only biomechanical and psychologic aspects of bracing was discussed here. Future research could also examine the proprioceptive effect of new designs.

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