

Comparison of Ankle Kinematics between Soft and Semi-Rigid Ankle Orthoses for Field-Sport Activities

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Abstract

Purpose of study: Examine ASO (soft) and Malleoloc semi-rigid stirrup (SRS) ankle orthosis designs on ankle kinematics during field-sport movements: sprint, one-legged jump, and 45-degree cut.

Participants: 13 competitive Ultimate players who regularly wore an ankle orthosis during physical activity.

Methods: ASO or Malleoloc orthosis was randomly assigned to each person. Kinematic data were captured while the participants performed several trials for each movement in a motion analysis laboratory. Participants repeated the protocol with the other orthosis.

Results: ASO allowed significantly more plantar-flexion during weight acceptance of the planting foot in cutting ($p=0.038$). In jumping, the Malleoloc allowed significantly more eversion-inversion range during stance ($p=0.048$) and eversion-inversion angular velocity from midstance to toe-off ($p=0.026$). Qualitative data also showed a significant preference for ASO.

Conclusion: Hypotheses that ankle inversion and eversion would be greater with the ASO; and plantar-flexion and dorsiflexion would be greater with the Malleoloc were refuted.

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List of Abbreviations

ASO Orthosis: Ankle stabilizing orthosis

ATFL: Anterior talofibular ligament

CFL: Calcaneofibular ligament

CNS: Central nervous system

COMET: Coordination and measurement training system

Donjoy ALP: Ankle ligament protector

DF: Dorsiflexion

F/S: Frames per second

PF: Plantar-flexion

PNS: Peripheral nervous system

PTFL: Posterior talofibular ligament

ROM: Range of motion

SEMO: Southeast Missouri agility test

SRS ankle orthosis: Semi-rigid stirrup ankle orthosis. The Malleoloc is a SRS orthosis.

ST: Stride time

Definitions

Flight time: The time between toe-off of one foot, and foot-strike of the opposite foot (also known as the period of non-support) (Hunter et al., 2004).

Goniometer: A device that measures angles.

Sprinting: Running at maximum capacity, with greater stride length and velocity than in jogging. The heel-strike in walking is replaced with a forefoot-strike. Sprinting form is different from running form, with the knee joint continuously flexed, even in stance phase (Novacheck, 1998).

Stride Time (ST): The time from foot-strike to foot-strike on the same foot.

Task 1: 10 m sprint

Task 2: Sprinting into a one-legged, push-off vertical jump and landing in any way/form.

Task 3: A cutting manoeuvre where the participant sprints, plants their orthosis-wearing foot, and pushes off at a 45° angle from the sprinting path.

Ultimate: Ultimate is a limited-contact team sport played with a 175 g flying disc. The object is to score points by passing the disc to a player in the opposing end zone, similar to an end zone in American football or rugby. While originally called Ultimate Frisbee, the sport is now officially called Ultimate because Frisbee is the trademark (Ultimate (sport), 2010).

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Chapter 1: Introduction

In sport and physical activity, the ankle is one of the most commonly injured joints of the human body (Beynnon et al., 2001; Mangwani et al., 2001). Ankle injuries occur at all levels of play to participants of all ages. A painful, stiff, or swollen ankle hinders ankle range of motion (ROM), preventing sport participants from performing the necessary movements to meet their athletic objectives. After an injury, individuals cannot fully rely on the ankle ligaments and muscles for strength and stability during re-integration into sport. Ankle orthoses can stabilize the ankle to prevent traumatic ankle inversion, eversion, or internal and external rotation by decreasing medial and lateral ROM (Eils et al., 2002). Ankle orthoses can also limit ankle flexion and extension (Wiley & Nigg, 1996), potentially affecting performance due to limited ROM (Green & Wight, 1990).

Ankle movement varies between activities. Therefore, different orthosis designs should be recommended for different athletic tasks and playing surfaces. Individuals also develop preferences in ankle orthoses based on perceived ankle support. An inappropriate orthosis may impede proper movement, provide insufficient protection, and hinder recovery during rehabilitation. For field sports, participants should be able to run, jump, plant, and change directions safely and with minimal resistance to the body and its movements.

Ankle orthoses may help increase the quantity and quality of physical activity for participants as they overcome barriers to daily exercise. Ankle orthoses give participants the opportunity to stay active despite having a lax, or injured, ankle.

Orthoses worn by sport participants are made of soft and semi-rigid materials. Soft orthoses consist of lace-up ankle sleeves. Semi-rigid orthoses have a semi-rigid plastic stirrup, a small platform on which the sole of the foot rests, and straps to secure the orthosis to the leg. A commonly used orthosis in North American Ultimate is the ASO (Ankle Stabilizing Orthosis) soft, lace-up orthosis (Parsley et al., 2013). Based on the results from a preliminary survey, many orthosis-wearing Ultimate participants chose an orthosis that was readily available, and the ASO is available in many local stores. Minimal research has been performed on proper ankle support during re-integration into sporting activities and finding the appropriate orthosis for the athletic demands of the participant.

This research will compare the biomechanical function of a soft and semi-rigid ankle orthosis during various field-sport tasks.

1.1 Rationale

Ankle injuries are one of the most common sport injuries and affect participants of all competition levels and age groups. These injuries often result in temporary, or even permanent, loss of sport participation. With the proper orthosis, field-sports participants can reduce the chance of ankle injuries and return to play with minimal restrictions to the movements needed to perform their athletic tasks.

A gap in the literature exists on the effects of ASO and Malleoloc orthoses on ankle kinematics and performance. The ASO has been observed as a common ankle orthosis for the sport of Ultimate in Canada and the United States, and in other activities (Parsley et al., 2013). While not as widespread in adoption, a SRS orthosis, such as the Bauerfeind

Malleoloc, could enable more plantar-dorsiflexion range of motion while maintaining ankle stability. Through kinematic analysis, a better understanding of the functional effects of soft and semi-rigid orthoses can be achieved.

1.2 Objective

The objective of this research is to examine the effects of soft and semi-rigid stirrup (SRS) ankle orthosis designs on ankle kinematics during movements repeatedly performed in field-sport athletics (sprint, one-legged jump, and cutting).

1.3 Hypotheses

1. Ankle inversion and eversion ROM will be greater when using a soft orthosis.
2. Plantar-flexion and dorsiflexion ROM will be greater when using a SRS orthosis.

1.4 Limitations

The field-sport movements, such as sprinting, one-legged jumping, and cutting were tested on floor tiles in a motion analysis laboratory. Therefore, participants were required to perform these movements with running shoes instead of cleats. A realistic testing environment would have been on grass, or turf, with cleats. In addition, some participants who were part of the experimental group had not worn their orthosis in running shoes before the testing period; they had only previously worn them in cleats.

The competitive Ultimate participants had various years of experience. This population sample was chosen because of the participant's regular anaerobic and power exercise

training. This convenience sample may not be transferrable to recreational participants. A post hoc analysis was performed to show that 27-38,000 participants would be required to achieve a 70% statistical power, depending on the outcome measure. In addition, participants were between the ages of 20-39, which represents the age range of participants in Ottawa's competitive Ultimate community. Performance differences could be expected between the younger and older participants in a group with a 19-year range.

The laboratory runway was limited in length; therefore, participants may not have reached maximum sprinting speed when passing through the capture volume. However, the sprint testing environment was consistent between trials and orthosis interventions (i.e., sprint speed should be the similar between trials, if both orthoses function similarly).

Dynamic stability could be an important element for gait confidence when moving with an ankle orthosis. Plantar pressure data were collected to investigate parameters that are sensitive to changes in dynamic stability; however, this analysis was omitted because the hypotheses on ankle ROM were answered with the 3D motion analysis. Small differences were found between orthoses; further analyses were not pursued since orthoses had similar kinematic effects on the ankle.

Chapter 2: Literature Review

2.1 Ankle and Foot Biomechanics

The ankle-foot bone structure consists of the distal tibia and fibula (Figure 2.1), and the talus, calcaneus, navicular, cuboid, three cuneiforms, five metatarsals, and 14 phalanges (Figure 2.2). The foot was created to bear weight and propel the body forward during locomotion, with the talus and calcaneus bearing most of the body weight. The medial and lateral longitudinal arches and the transverse arch help with shock absorption and act as a spring to help propel the body forward (Figure 2.3) (Kapit & Elson, 2002).

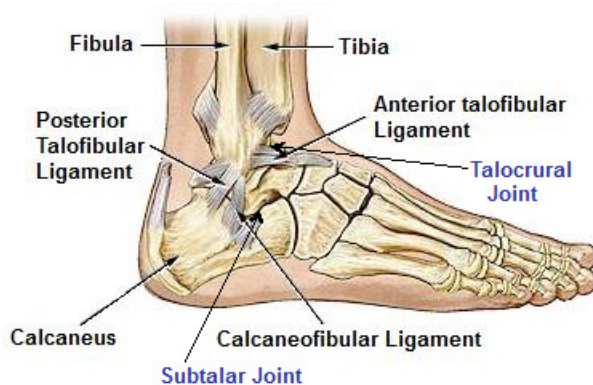


Figure 2.1. Lateral view of the ankle bones and ligaments (Adapted from Nucleus Communications Inc., 1998).

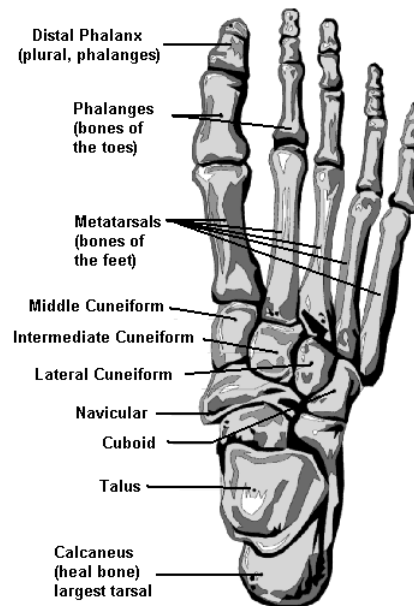


Figure 2.2. Bones of the foot (Adapted from X Projekt, 2010).

The talocrural joint is a hinge joint, commonly known as the ankle joint (Figure 2.1). The subtalar joint allows the leg to rotate on the weight-bearing foot (Tropp, 2002) and is often responsible for joint laxity. The ankle ligaments and anatomical alignment play important roles in preventing ankle injury before muscle pre-activation since ankle reflexes may not react in time to prevent serious ankle inversion (Hume & Gerard, 1998).

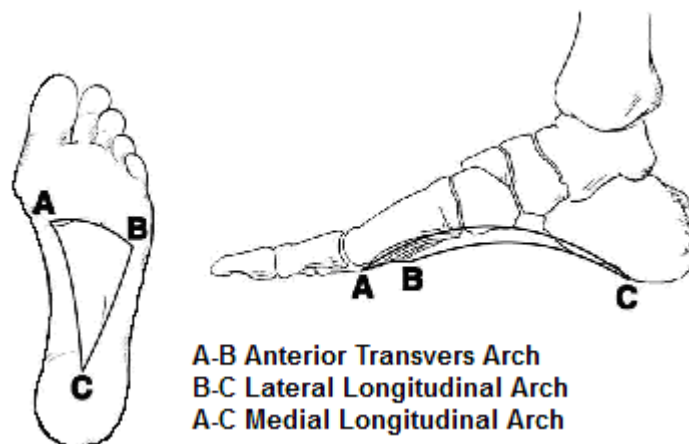


Figure 2.3. The three arches of the foot (Adapted from Toms Underground, 2012).

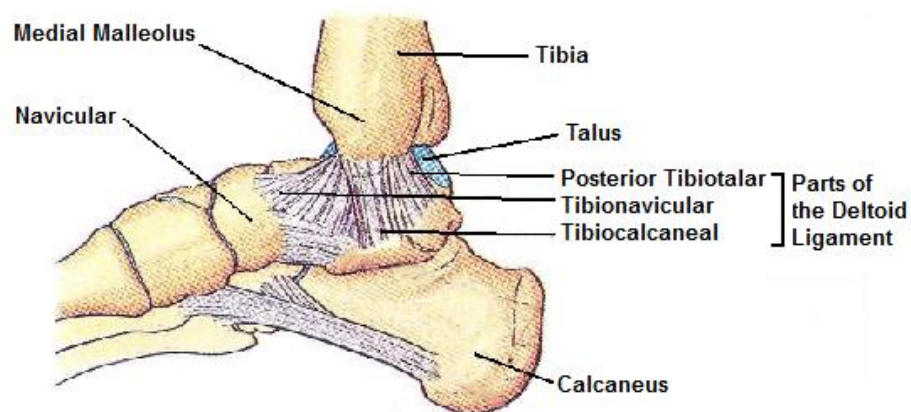


Figure 2.4. Medial view of the deltoid ligament (posterior tibiotalar, tibionavicular, and tibiocalcaneal ligaments) (Adapted from AMC Medical Systems, n.d.).

Ankle ligaments include the anterior talofibular ligament (ATFL), calcaneofibular ligament (CFL), posterior talofibular ligament (PTFL) (Figure 2.1), and deltoid ligaments (Figure 2.4). The deltoid ligaments prevent excessive ankle eversion and are the strongest ligaments of the foot, which helps explain why ankle eversion sprains are the least common ankle injuries (Marieb, 2004). Plantar-flexion and internal rotation pull on the ATFL and CFL (Lynch, 2002). Inversion injuries occur when the ATFL and CFL are not strong enough to resist the force applied to the ankle, pushing the ankle past its natural ROM.

The ankle plantar and dorsiflexes in the sagittal plane, inverts and everts in the frontal plane, and internally and externally rotates in the transverse plane (*Figure 2.5*). Typical ranges of motion for healthy adults are summarized in Table 1. Dorsiflexion and external rotation values are similar across studies, but values for other motions vary.

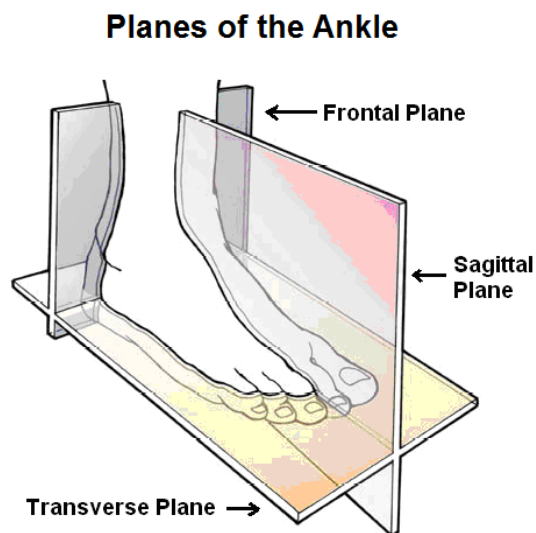


Figure 2.5. Anatomical planes of the foot (Adapted from Ojus, 2011).

Table 1. *Ankle ROM (degrees) for able-bodied people (standard deviation in brackets).*

Study	Inversion	Eversion	Plantar flexion	Dorsi flexion	Internal Rotation	External Rotation
Siegler et al., 1997	33.7 (7.79)	25.6 (4.10)	36.9	25.8	24.9 (8.18)	32.8 (4.77)
Grimston et al., 1993	21	17	48	26	40	36
Eils et al., 2002	39 (9)	23 (7)	43 (5)	25 (2)	36 (6)	37 (6)

2.2 Ankle Assessment

Many approaches have been developed to assess the ankle. The predominate method is the Anterior Drawer test and Talar Tilt test.

2.2.1 Anterior drawer test

The Anterior Drawer test assesses ATFL integrity by examining talus displacement in the sagittal plane (Lynch, 2002). The participant sits with the knee flexed to relax the gastrocnemius. The examiner firmly holds the bottom of the shank in one hand, grasps the heel in the other hand, and pulls forward with the hand holding the heel (Figure 2.6). If the foot easily slides forward when holding the shank, the ATFL is lax. Both ankles must be evaluated and compared to rule out genetic factors.

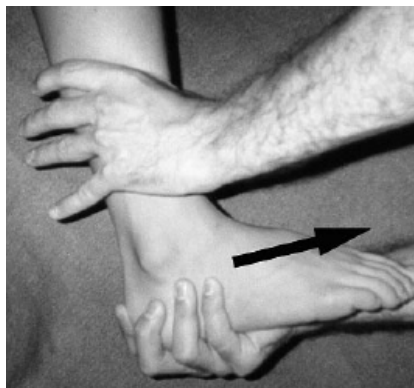


Figure 2.6. Anterior Drawer test (Lynch, 2002).

2.2.2 Talar Tilt Test

The Talar Tilt Test detects CFL laxity by examining the angle produced by the tibial plafond and the dome of the talus when forceful passive inversion is applied to the ankle (Figure 2.7, Figure 2.8) (Lynch, 2002).



Figure 2.7. Talar Tilt Test (Slimmon & Brukner, 2010).

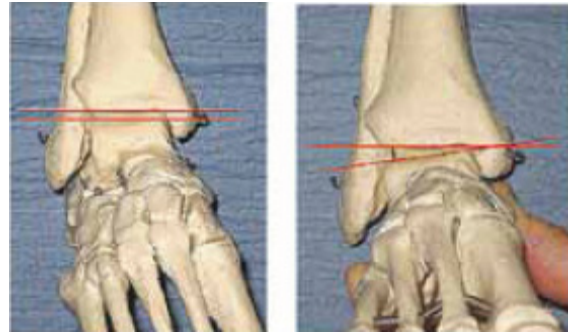


Figure 2.8. Talar Tilt Test (Lynch, 2002).

The talar tilt test is performed with the participant sitting with the leg relaxed and the ankle in neutral position. The examiner firmly holds the distal end of the shank with one hand while cupping the heel with the other hand, trying to invert the heel with respect to the tibia. Laxity in both ankles is compared. More than 10° difference in laxity between ankles is considered abnormal (Lynch, 2002).

2.3 Ankle Injury in Field Sports

Contact sports and sports with a high jumping rate have an increased incidence of injury (Backx, 1991). Ankle injuries, especially to the lateral ankle ligaments (Chan et al.,

1993), are the most common sports injury (Beynon et al., 2001; Mangwani et al., 2001; Rosenbaum et al., 2005). Many injuries occur in competitive sports because athletes spend more time training and they play at a high intensity level. Approximately 75% of sport participants are likely to injure their ankle(s) more than once (DiStefano et al., 2008; Elkstrand & Tropp, 1990; Jones et al., 1993; Milgrom et al., 1991; Yeung, et al., 1994), especially a previously injured ankle (Ekstrand & Gilquist, 1983; Tropp et al., 1985).

Boyce and Quigley (2004) found that ankle ligament sprains were the most common sports injury, resulting in 19% of all sports injuries reported to accident and emergency departments in the United Kingdom. In Ireland, field-sport participants, particularly those with ankle injuries, made up 19% of emergency department patients (Murphy et al., 1992). Ekstrand and Tropp (1990) discovered that 17%-21% of soccer injuries involved the ankle, among 41 different teams. When looking at the causes of soccer injuries, 12% resulted from contact with another player (Hawkins & Fuller, 1999) and 26% (Lüthje et al., 1996) to 59% (Hawkins & Fuller, 1999) occurred without any player contact. Movements causing non-contact ankle injuries were running and turning, or pivoting (Hawkins & fuller, 1999; Hawkins et al., 2001). Although ankle injuries are common, most of these injuries are benign. The positive effects of exercise certainly outweigh the likelihood of sustaining an ankle injury. However, the incidence of such injuries needs to decrease (Tropp, 2002).

The first ankle sprain leads to a predisposition for recurrent ankle sprains, chronic ankle joint instability, and joint degeneration (Surve et al., 1994). Reoccurrence has been reported in 40%-70% of ankle injury cases (Gerber et al., 1998; Yeung et al., 1994). Ankle

inversion injuries cause functional ankle instability in 15-60% of cases (Kannus & Renström, 1991). Injury of the dominant ankle is more than twice as likely as compared with the non-dominant ankle (Yeung, et al., 1994). Most ankle injuries occur during excessive ankle inversion and ATFL strain, often caused when the foot is in plantar-flexion and internally rotated (Figure 2.9) (Arnheim & Prentice, 1993; Callaghan, 1997; Colville et al., 1990; Garrick & Requa, 1973; Wikstrom & Anderson, 1997).

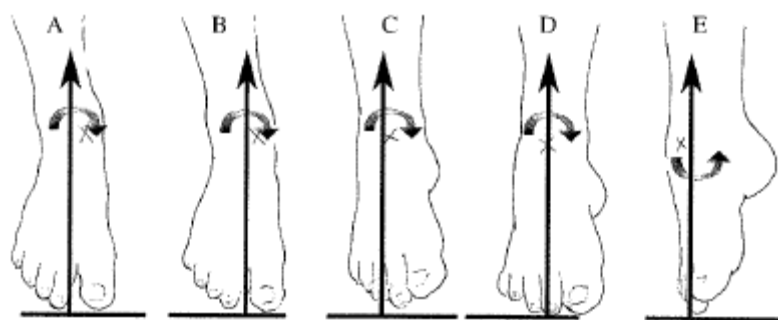


Figure 2.9. Foot position for inversion sprains (Tropp, 2002).

Ankle injuries can be debilitating and can prevent sport participants from being active for long periods, leading to feelings of frustration. Reducing the incidence of ankle injuries will diminish the loss of team continuity and playing flow during a game. In addition, a decrease in ankle injuries will save the time of both the sport participants and the organization for proper care and rehabilitation of the injured athlete (Nielsen & Yde, 1989).

2.4 Ankle Injury Mechanisms

Ankle injuries are caused by intrinsic and extrinsic factors. Intrinsic factors are characteristics of the sport participant, such as age, sex, strength, range of motion, joint

stability, generalized joint laxity, and predisposition to getting ankle injuries. These factors can occur due to previous ankle injuries or genetics (Baumhauer et al., 1995). An increase in the participant's age increases the chances of sustaining an injury by 15-30 times. However, the chances of sustaining an injury also increase with intensity of play (Keller et al., 1987). Intrinsic factors that increase susceptibility to ankle injuries include joint instability, muscle tightness, lack of training (Ekstrand et al., 1983), inadequate rehabilitation (Ekstrand & Gillquist, 1983; Keller et al., 1987; Stasinopoulos, 2004), and poorly executed cuts where the foot is inverted and plantarflexed before, or at, ground-contact (Garrick, 1977; Wright et al., 2000). Having a previous ankle sprain is a major intrinsic factor in the likelihood of getting another ankle sprain (Ekstrand & Gillquist, 1983; Keller et al., 1987; Tropp et al., 1985). Recurring ankle sprains can lead to chronic lateral instability, which leads to a prolonged reaction time at the ankle, in comparison to participants who have not had an ankle injury (Löfvenberg et al., 1995).

Chronic ankle instability can cause ankle pain during activity, consistent post-activity ankle swelling, and the feeling of the ankle giving way, which may lead to ankle re-injury (Nitz et al., 1988). Muscle imbalance plays a more important role in predicting an ankle injury, compared to muscle weakness (Lentell et al., 1990). A smaller dorsiflexion-to-plantar-flexion strength ratio, or an elevated eversion-to-inversion strength ratio, leads to a higher incidence of inversion ankle sprains (Baumhauer et al., 1995).

Chronic ankle instability results from mechanical and functional mechanisms. Mechanical instability is when the ankle ROM goes beyond typical physiological limitations

(joint laxity) due to ligamentous laxity or nerve injury (Freeman et al., 1965; Tropp, 2002; Tropp, 1985; Vaes et al., 1998). Functional instability, an intrinsic factor for the susceptibility of ankle sprains, is caused by the combination of faulty functional and mechanical factors. An individual with functional instability may have a subjective feeling of instability or weakness due to previous ankle sprains (Freeman et al., 1965). Functional instability is caused by proprioceptive and neuromuscular deficits, such as reduced ability to detect joint position and passive movement at the ankle, as well as reduced postural control and reflex speed (Freeman et al., 1965; Jerosch et al., 1995; Tropp, 2002; Vaes et al., 1998), especially the reflex speed of the peroneus longus (Konradsen. & Bohsen, 1991). However, a study by Konradsen et al. (1998) found that injury to the lateral structures of the ankle does not cause a reduction in reflex reaction. Individuals with functional instability have increased postural sway and decreased kinesthetic sensation (Gauffin et al., 1988; Tropp, 1985), sometimes caused by nerve deafferentation in the ankle complex during the original ankle injury (Refshauge et al., 2000). In addition, peroneal muscle weakness and chronically unstable ankles are related (Hartsell & Spaulding, 1999). Donatelli et al. (1996) described proprioception as an awareness of posture, movement, change in equilibrium, and mechanical inertia that cause pressure and strain at the joint, allowing participants to sense joint position.

Mechanical instability can cause functional instability (Vaes et al., 1998). Cutaneous, joint, and muscular receptors relay information from the peripheral nervous system (PNS) to the central nervous system (CNS) to increase motor control. Feuerbach et al. (1994) discovered that anesthetizing the ankle's lateral ligaments did not affect ankle proprioception

when participants were asked to match reference positions with their ankle. Hertel et al. (1996) reported no significant effect on centre of balance and postural sway when anesthetizing the ATFL. These two findings suggest that cutaneous receptors may be more effective than ligament receptors in providing proprioceptive information at the ankle.

Extrinsic factors also cause ankle injuries, for example, running and landing from a jump on an uneven playing surface (Garrick, 1997). Extrinsic factors include the type of sport, playing time, level of competition, equipment, and environmental conditions (Baumhauer et al., 1995).

2.5 Orthoses for Ankle Injury Prevention and Rehabilitation

Ankle orthoses are commonly referred to as ankle braces (Metcalf et al., 1997; Sharpe et al., 1997; Eils et al., 2002; Paris, 1992; Alves et al., 1992) and are mostly fabricated from plastics and other synthetic materials. These assistive devices can be worn on the ankle for prophylactic purposes, to reduce both the frequency (Surve et al., 1994; Sharpe et al., 1997; Cordova et al., 2000) and severity (Shaw et al., 2008) of ankle injuries that can occur during sport participation, or during rehabilitation after an ankle injury (Osborne & Rizzo, 2003; Boyce et al., 2005). Although the most important feature of an ankle orthosis is its ability to support the ankle, other factors must be considered when selecting an appropriate orthosis, such as perceived comfort, support, performance restriction effects, and objective effects on performance (Beriau et al., 1994).

Athletes who have had a moderate or severe ankle sprain should wear an ankle orthosis during physical activity for at least six months following their injury (Thacker et al., 1999).

Sport participants that lack confidence in their ankle's ability to support their weight during sport movements could wear an ankle orthosis even if they have not had an injury, or if their injury occurred in the distant past. Orthoses are worn during the healing process but they can also enhance ankle stability and performance in non-injured sports participants (Makihara, 2004). Ankle orthoses are needed to protect ankle ligaments when the ankle ROM exceeds normal range. The orthosis should provide a balance between protection and performance (Robertson et al., 1986).

2.6 The Importance of Orthoses for Sport Participation

Gross & Liu's (2003) found that semi-rigid orthoses are effective for preventing injury and re-injury without hindering mobility and functionality, although testing on new ankle orthoses is required. Pedowitz's (2008) evaluated a vertical horseshoe-shaped orthosis by recording orthosis and injury details for seven years. Of 13,500 female college volleyball players who used a prophylactic orthosis, only one ankle injury occurred. Although the prophylactic orthoses prevented ankle injury for these volleyball players, it did not affect one-legged balance in non-injured participants (Hardy, 2008). In summary, semi-rigid orthoses prevented injury but still allowed adequate ROM to perform athletic movements.

Cordova et al. (2000) believed that long-term orthosis use does not affect peroneus longus muscle latency during sudden inversion in normal subjects, therefore, a player's body would not become dependent on the orthosis for stability. However, Cordova et al. (2000) only tested for a two-month period. In a preliminary questionnaire, participants stated that they rely on the orthosis all year long for contact sports, thereby supporting the need for

long-term tests. In the Kernozek et al. (2008) study, results were inconclusive for an SRS orthosis to enhance ankle proprioception by affecting ankle muscle perturbation. Rosenbaum et al. (2005) reported insignificant results between 10 different SRS and lace-up orthoses after objective testing on vertical jumping height, single leg hopping time, sprint time and side-cut time, but significant subjective differences on orthosis comfort. Participants perceived SRS orthoses to be significantly easier to handle and provide more support, and lace-up orthoses to be more comfortable and allow less performance impairment. Rosenbaum et al. (2005) claimed that the orthosis-wearers would be satisfied if the orthosis is comfortable and prevents injury.

2.7 Types of Orthoses

In this research, orthoses are classified in two general categories: soft and semi-rigid. Soft orthoses compress the joint with a tight-fitting, wide elastic band, or a lace-up sleeve, to help with joint effusion or to decrease swelling. The bands, or sleeves, are made of synthetic fabric, or leather. Materials that are more rigid provide medial and lateral support. Soft orthoses are also worn to support chronically unstable ankles (Jerosch et al., 1995).

Semi-rigid orthoses stabilize the ankle during exercise (Jerosch et al., 1995). Two semi-rigid plastic splints are fitted over the medial and the lateral aspects of the ankle. The stirrup piece is padded on the inside with air, foam or gel bags. The stirrup is fixed to the limb with straps. Ankle stirrup orthoses are constructed to provide medial and lateral joint stability for early ambulation, while providing increased collateral pressure for diminishing edema. Semi-rigid orthoses are also worn to support chronically unstable ankles.

Ankle orthoses should be tightened before activity and, if needed, during activity to gain maximal stabilizing benefits (Rovere et al., 1988; Paris et al., 1995). Individuals who are likely to resume activity during the acute phase of their ankle injury, and are not likely to follow instructions, might benefit from the Aircast orthosis because this orthosis is easy to assemble and wear in the shoe (Guskiewicz et al., 1999). Semi-rigid orthoses with a stirrup design are recommended if quick and easy orthosis application is the primary concern; soft orthoses are recommended if comfort is the primary concern. An optimal orthosis should be both comfortable and easy to apply. Some SRS orthoses may wear out shoes and are often not compatible with other exercise or rehabilitative equipment. Sport participants should assess their playing conditions before selecting an orthosis (Rosenbaum et al., 2005).

2.7.1 Soft orthosis designs

2.7.1.1 *Kallassy*

The Kallassy is a nylon-lined neoprene sleeve with two lateral non-stretch Velcro straps that are designed to resist ankle inversion (Figure 2.10). One of the straps helps lock the ankle in a neutral position (#6 on Figure 2.11), and the other one at the top of the orthosis wraps horizontally around the shank to secure the lateral straps (NeaTec, “n.d.”; SupportsUSA, 2010; Alves et al., 1992). The Kallassy provides warmth and compression to the ankle, allows full plantar and dorsiflexion, fits in most athletic and dress shoes/boots, and can be adjusted while in the shoe. This orthosis is used for lateral ligament sprains, ankle support, prophylactic reasons, recurrent ankle injuries, after surgery and in conjunction with taping for additional support (SupportsUSA, 2010).

Kallassy Orthosis



Figure 2.10. Kallassy orthosis (Adapted from Sportstek, 2010).

Kallassy Strapping System

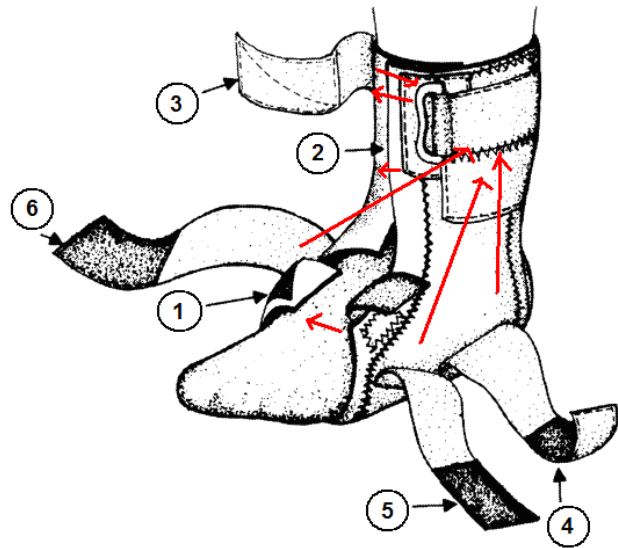


Figure 2.11. Kallassy strapping (Adapted from NeaTec, n.d.).

2.7.1.2 Swede-O Universal

The Swede-O Universal is a lace-up sleeve with an elastic nylon tongue (Figure 2.12). Ankle support is reinforced with medial and lateral panels, placed between the fabric layers. Extra plastic stirrup pieces are available for added support (Alves et al., 1992).

The Swede-O



Figure 2.12. The Swede-O. (Adapted from Kiwi Rehab, 2013)

2.7.2 ASO

The ASO lace-up sleeve is made of thin ballistic nylon with two opposing non-stretch stabilizing figure-8 straps that attach at the medial and lateral aspects of the shank, locking the heel into place. The elastic cuff closure at the bottom of the shank covers the laces, the figure-8 straps, and secures the orthosis to the leg (Figure 2.13, Figure 2.14).

The ASO orthosis is comfortable, reusable, and can be tightened within a shoe (Achilles Medical, 2008). The ASO is worn during rehabilitation, or to prevent acute ankle sprains. This orthosis is meant to reduce inversion or eversion injuries/re-injuries and can be worn on right or left ankles, with or without shoes (Achilles Medical, 2008).



Figure 2.13. ASO Orthosis (Adapted from Athlete's Care, 2009).

ASO Strapping System



Figure 2.14. ASO strapping (Adapted from Abrace.com, 2008).

2.7.3 Semi-rigid orthosis designs

2.7.3.1 Air-Stirrup

The Aircast Air-Stirrup is made of two polymer strips that are attached to a plastic heel pad to form a stirrup (Figure 2.15). The heel pad is placed under the calcaneus and the strips

extend vertically from the base, covering the malleoli and extending approximately six inches above the ankle. The Air-Stirrup pieces are lined with an inflatable, flexible, polymeric air bladder to protect the malleoli from irritation and discomfort (Pienkowski et al., 1995; Boyce et al., 2005). The bladders exert alternating pressures during plantar-flexion and dorsiflexion (Boyce et al., 2005), and compress the ankle to reduce edema, thereby accelerating rehabilitation (DJO Global, 2010). Two Velcro straps are wrapped horizontally around the lower shank, above the ankle. These straps secure the Air-Stirrup to the foot, ankle and shank (Verbugge, 1996; Alves et al., 1992).

The Aircast Air-Stirrup is designed to prevent inversion and eversion. The small orthosis design allows the Aircast to fit in shoes for protected early weight-bearing during rehabilitation (DJO Global, 2010).



Figure 2.15. Aircast Sport Stirrup (Boyce et al., 2005).

2.7.3.2 Donjoy ALP (ankle ligament protector)

The Donjoy ALP is made of a rigid plastic heel cup, fused into a vertical strut along the posterior aspect of the lower leg (Figure 2.16). A calf cuff is located at the top of the

rigid piece, inferior to the calf. Velcro holds the heel cup to the inside of the shoe (Gross et al., 1994). This orthosis restricts inversion and eversion (Greene & Hillman, 1990).

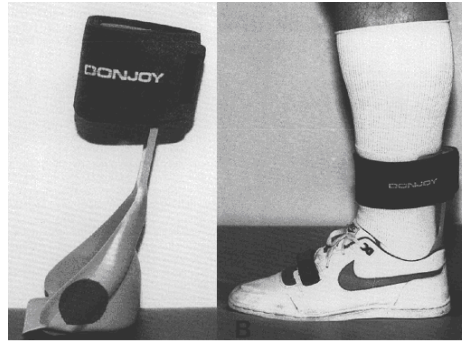


Figure 2.16. Donjoy ALP (Greene & Hillman, 1990).

2.7.3.3 Malleoloc

The Malleoloc orthosis is a flexible polypropylene stirrup, cushioned with a thin layer of foam-like material. A lateral stirrup runs along the fibula, anterior to the lateral malleolus. A medial stirrup runs along the tibia, posterior to the medial malleolus (Figure 2.17). The anterolateral stirrup restricts forward movement of the talus (Bauerfeind USA Inc., 2008). The Malleoloc has two straps:



Figure 2.17. Malleoloc (Adapted from Bauerfeind Canada, 2013).

one on the lower shank above the ankle and one in a ‘figure-8’ around the ankle (Baier & Hopf, 1998). The Malleoloc is worn for the rehabilitation of injuries to the lateral ligaments, chronic ligament insufficiency, postoperative rehabilitation, and for prophylactic use. The Malleoloc, which can be worn inside shoes or cleats, counteracts supination and lateral twisting of the ankle (Bauerfeind USA Inc., 2008).

2.8 Biomechanical Evaluation of Ankle Orthoses

Many studies have evaluated ankle kinematics with an orthosis during various sport movements. These studies evaluated the ability of the orthosis to stabilize the ankle in different physical situations, for sport-related movements. Passive and active ROM with ankle orthoses has also been tested using: specialized test machines, tilting platforms, and motion analysis of sport-specific movements. Ground-reaction force tests have been used to observe the effects of ankle orthoses on stability during weight-bearing. General sport performance has also been observed to determine the effects of ankle orthoses on movement outcomes and hindrances. An ankle orthosis should restrict ROM, thereby preventing ankle damage, but not impede sport performance.

2.8.1 Passive ROM

Passive ROM testing involves a person, or machine, moving an individual's ankle. Therefore, minimal muscular forces act on the ankle to influence ROM. Joint ligaments and bones create the only substantial limitations to movement in passive ROM testing, prior to the application of an ankle orthosis. Orthosis stiffness and design also influence ROM.

Eils et al. (2002) evaluated passive ROM with a custom-built tilting platform. The Kallassy and Kallassy S significantly reduced inversion by 46% and the semi-rigid Air Gel Sport Stirrup reduced ROM by 63%. The Malleoloc provided significantly less stability to the ankle in comparison to soft orthoses, allowing 70% eversion and 60% plantar-flexion of the condition without orthoses. In these studies, soft ankle orthoses restricted ROM to a greater degree prior to activity, before orthosis materials stretched.

Greene & Hillman (1990) found that the Donjoy orthosis restricted passive pre-activity ROM by 42% and post-activity ROM by 37%. Greene & Hillman (1990) had softball players wear orthoses and tested passive ROM at different times throughout the practice. The Swede-O, Aircast Sport Stirrup, and Donjoy ALP all significantly reduced passive pre-exercise inversion and eversion. However, eversion support decreased after 20 minutes for the Swede-O and the Aircast Sport Stirrup, and passive inversion support was lost for the post-practice measurement. The Aircast Sport Stirrup was the only orthosis that significantly increased running times across the bases. Gross et al. (1994) found that the Donjoy ALP significantly restricted passive inversion before and after 10 minutes of figure-8 running. Restricting passive ROM is only helpful if it does not jeopardize performance.

Paris et al. (1995) recorded ankle ROM after 15, 30, 45, and 60 minutes of activity on a treadmill, using Swede-O or semi-rigid Subtalar Support devices. Both Swede-O and Subtalar Support orthoses restricted ankle ROM in all directions before activity and reduced inversion support after 15 minutes of exercise. The Swede-O reduced plantar-flexion support after 30 minutes of exercise, and eversion support after 60 minutes. The Subtalar Support reduced plantar-flexion support after 15 minutes of exercise. Kimura et al. (1987) recorded ankle motion on a 35° tilting platform for participants wearing the Aircast Sport Stirrup. In comparison to an orthosis-free group, the Aircast Sport Stirrup group reduced ankle inversion by 9.8° (33%).

These studies showed that ankle orthoses restrict passive ROM before exercise, but the prophylactic effects decrease as the orthosis stretches during exercise. Generally, orthoses

worn during sport will stretch due to the forces from movement, contact with the ground, or contact with another object. Therefore, evaluation in dynamic situations may be more appropriate for testing the effectiveness of orthosis ROM restriction during physical activity.

2.8.2 Motion analysis

Motion Analysis is a way of measuring active ankle ROM produced by individuals wearing orthoses, during sport-specific movements. Motion analysis helps researchers record the kinematic effects of the orthosis in action.

Gudibanda & Wang (2005) looked at cutting manoeuvres in participants wearing a soft ASO, without shoes, during forward lateral cutting (45° cut) and sideward lateral cutting (horizontal side-to-side movement). During forward lateral cutting, the ASO significantly decreased inversion by 48% and plantar-flexion by 41%. In sideward lateral cutting, plantar-flexion was decreased by 48%. However, participants might have performed their cuts at less than 100% of maximal capacity since they were not wearing shoes, which would have made the testing more realistic.

Martin & Harter (1993) recorded walking and running on a treadmill for 20 minutes at an incline of 8.5° while subjects wore the Swede-O or Aircast Sport-Stirrup without shoes. Both the Swede-O and the Aircast Sport-Stirrup significantly decreased ankle inversion before and after walking and running on a treadmill. In future studies, observing the effects of ankle orthoses on foot movement during treadmill exercises should be done with participants who are wearing shoes, since the general population wear running shoes on treadmills. These studies show that ankle inversion and plantar-flexion are restricted by

several orthoses during physical activity, thereby restricting the mechanisms of the most common ankle injury- inversion sprains.

2.8.3 Athletic Performance Evaluations with Ankle Orthoses.

Athletic evaluations with ankle orthoses helps researchers determine if ankle orthoses impede performance. Although ankle stability, or perceived ankle stability, is important to those with lax ankles, performance should not be sacrificed to gain ankle stability.

Burks et al. (1991) compared the broad jump, vertical leap, 10 yard shuttle run, and 40 yard sprint between the Swede-O and Kallassy orthoses. The Swede-O decreased the vertical jump performance by 4.6%, the broad jump by 3.6%, and the sprint by 3.2%. The Kallassy decreased the vertical jump by 3.4%. Gross et al. (1997) recorded their participant's performance in a 40-meter sprint, a figure-8 run, and a vertical jump height when wearing the Aircast Sports Stirrup and the Donjoy ALP. Both orthoses did not significantly affect performance.

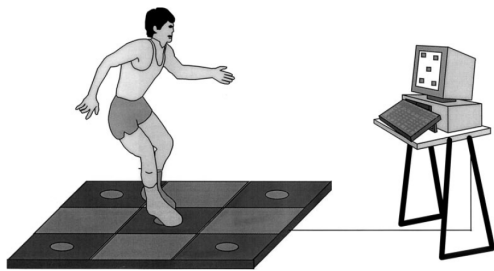


Figure 2.18. COMET (coordination and measurement training) (Jerosch et al., 1997).

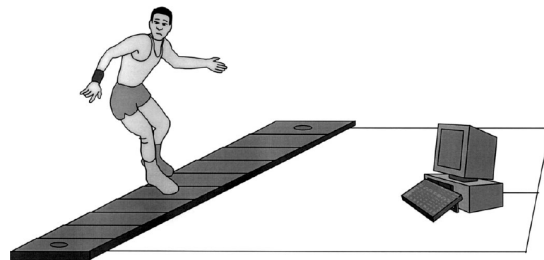


Figure 2.19. Japan Test with COMET (Jerosch et al., 1997).

Jerosch et al. (1997) used the COMET (coordination and measurement training system) with active and passive plates to measure quickness and reaction time. Participants stepped on an active plate that changed colour. The COMET recorded the time of contact and then the plate returned to its original colour (Figure 2.18). Participants performed a single-leg jump test and a Japan test. In the Japan test, the COMET plates were positioned in a 4 m line, with two active outer plates. The participants sidestepped as fast as possible from one active outer plate to the other (Figure 2.19). The total time, standing time on each plate, and stepping time between the two plates were measured. The COMET tests were performed with the soft Ligafix Air Brace, Aircast Sport Stirrup, and Malleoloc. All orthoses improved reactionary lateral/side-to-side movement. The Aircast Sport Stirrup and the Malleoloc significantly improved single-leg jump test reaction time compared to having no orthosis. In addition, the Aircast Sport Stirrup helped quicken the supination time and the Malleoloc helped quicken pronation time during the single-leg jump compared to having no orthosis.



Figure 2.20. McDavid, New Cross and Swede-O soft, lace-up orthoses (Adapted from Paris, 1992).

Metcalf et al. (1997) asked participants to wear a Swede-O orthosis when measuring their jump height and recorded results from the SEMO (Southeast Missouri) agility test. Passive ROM was also recorded using a hand-held goniometer. The Swede-O decreased passive inversion, plantar-flexion, dorsiflexion, and reduced vertical jump. Paris (1992) recruited elite soccer players to perform a 50-yard sprint, a dynamic balance test, the SEMO Agility Test, and a jumping test with the soft New Cross, Swede-O, and McDavid orthoses (Figure 2.20). The only significant finding was that the New Cross reduced vertical jump height by 5.4%. Rosenbaum et al. (2005) looked at maximum vertical jump height single-leg hopping test on a self-constructed wooden platform that featured four inclined plates: 15° inversion, eversion, plantar-flexion and dorsiflexion (Figure 2.21), and combined straight and slalom sprint sidesteps with a cutting manoeuvre on a force platform. Participants were tested with soft (Kallassy, Kallassy S, Fibulo Tape and Dynastab) and semi-rigid (Aircast Sport Stirrup, Air Gel, Air Brace, Ligacast Anatomic and the Malleoloc) orthoses. No significant differences were reported. However, the participants perceived the semi-rigid orthoses as restricting performance in all sections of the agility course, more than the soft models, especially during the hopping test and the curve run.

Verbugge (1996) asked male athletes to perform an agility run, a 40-yard sprint, and a vertical jump with the Aircast Sport Stirrup. The significant effect was that jump distances averaged 1.52 cm lower with the orthosis. Beriau et al. (1994) recorded high school student timed agility runs, incorporating forward and backward running, lateral shuffling, and directional changes. The agility course times with the Aircast Training Brace were significantly lower than with the Donjoy ALP.



Figure 2.21. Single-leg hopping test (Rosenbaum et al., 2005).

Wiley & Nigg (1996) recorded jumping and figure-8 tests for participants wearing a Malleoloc orthosis, as well as passive and active ROM pre- and post-exercise. The Malleoloc significantly reduced active pre-exercise plantar-flexion by 6° (16%), dorsiflexion by 3° (13%), inversion by 11° (44%), and eversion by 3° (24%). The Malleoloc significantly reduced active post-exercise plantar-flexion by 4° (11%), inversion by 9° (35%) and eversion by 2° (21%). However, the Malleoloc did not have a significant effect on jumping and figure-8 test performances.

2.9 Observational Studies on Injury Rates

Recording ankle injury rates with ankle orthoses helps determine if wearing an ankle orthosis reduces the incidence of ankle injuries.

Sharpe et al. (1997) found that the Swede-O significantly reduced reoccurrences of ankle injuries. Surve et al. (1994) randomly assigned soccer players with or without a history of ankle sprains to a control group and an Aircast Sport Stirrup group, respectively, and

recorded the incidence of ankle sprains and hours of practice/playing. Results showed a significant reduction in ankle sprain incidence for soccer players in the Aircast Sport Stirrup group with an ankle sprain history (0.46/1000 playing hours) compared to those with a previous history of ankle sprains in the control group (1.16/1000 playing hours). Observing injury prevention results with participants who have had an ankle injury is very important, since those who have injured their ankle are prone to re-injury (Surve et al., 1994).

2.10 Orthosis Comfort

2.10.1 Swede-O Universal (soft)

The Swede-O was perceived as the third most supportive and comfortable orthosis, next to the Kallassy and Aircast Sport Stirrup (Alves et al., 1992). Participants in the study by Burks et al. (1991) also found the Swede-O to be less comfortable than the Kallassy, and perceived a decrease in performance while wearing the orthosis. Beriau et al. (1994) found that the Swede-O provided excellent support and comfort. This orthosis was one of the least restrictive orthoses, for speed and quickness performance, compared the semi-rigid Aircast Sport Stirrup and Donjoy ALP. Forty two percent of the subjects preferred wearing the Swede-O orthosis. However, Greene & Wight's (1990) participants rated the Swede-O as the second-preferred orthosis next to the Donjoy ALP.

2.10.2 Kallassy (soft)

The Kallassy orthosis was perceived as the most comfortable by 44% of participants, the second-most supportive next to the semi-rigid Aircast Sport Stirrup. The Kallassy was

voted the orthosis of choice by 41% of participants (Alves et al., 1992). Participants in Burks et al.'s (1991) study also found the Kallassy to be more comfortable and to restrict performance less than the Swede-O.

2.10.3 ASO (soft ankle stabilizing orthosis)

The ASO was rated 7.4 - 8.1 out of 10 for comfort, support, ease of application, and effect on performance during cutting manoeuvres in a study where participants wore the orthosis and no shoes (Gudibanda & Wang, 2005).

2.10.4 Aircast Sport Stirrup (semi-rigid)

The semi-rigid Aircast Sport Stirrup was perceived as the most comfortable by 41% of participants, provided the most support, and was rated as the orthosis of choice by 33% of participants in comparison to the Swede-O, Kallassy and Donjoy ALP orthoses (Alves et al., 1992). Participants in the study by Beriau et al. (1994) found that the Aircast Sport Stirrup provided excellent support and comfort. This orthosis was perceived to be the least restrictive for speed and quickness in comparison with the Swede-O and Donjoy ALP. In Verbugge's (1996) study, 76.9% of participants rated the Aircast Sport Stirrup as comfortable or very comfortable. In Gross et al.'s (1997) study, 74% of participants rated the Aircast Sport Stirrup as being more comfortable than the Donjoy ALP. However, one of 23 participants said that the Aircast Sport Stirrup's anterior trim line dug into the skin and the foot slid in the shoe because of the orthosis. Two participants developed redness or a blister on the lateral aspect of foot during testing with the Aircast Sport Stirrup and three participants said that the orthosis was bulky inside the shoe.

2.10.5 Donjoy ALP (semi-rigid ankle ligament protector)

The semi-rigid Donjoy ALP was rated as the most preferred orthosis in comparison to the Swede-O and the semi-rigid Air-Support (Greene & Wight, 1990). However, participants of Alves et al.'s (1992) study found the Donjoy ALP to offer the least support and comfort by 79% and 71%, respectively, in comparison to the Swede-O, Kallassy, and Aircast Sport Stirrup. The Donjoy ALP was the only orthosis not selected as the orthosis of choice by any of the participants. Similar results were found by Beriau et al. (1994) with respect to comfort. Only 9% of participants preferred the DonJoy ALP to the Swede-O and the Aircast Sport Stirrup. However, in Gross et al.'s (1997) study, 13% of participants rated the Donjoy ALP as being more comfortable than the Aircast Sport Stirrup. Three of 23 participants said they developed redness on the heel area under the calf-cuff or lateral malleolus and that the heel cup pushed into the arch of their foot. These participants also said their foot slid within the Donjoy ALP and that the orthosis restricted their movement. Four participants said their foot was pushed forward into the shoe. In an earlier study with the Donjoy ALP, one of 16 participants developed blisters on the posterior aspect of both heels during testing, two reported irritations on the posterior aspect of the calf under the calf cuff, and three participants reported excessive rubbing on the lateral malleolus (Gross et al., 1994).

2.10.6 Air-Support (semi-rigid)

Participants in Greene & Wight's (1990) study rated the semi-rigid Air-Support as the least-preferred orthosis in comparison to the Swede-O and the Donjoy ALP. Results from Rosenbaum et al.'s (2005) study show that the soft orthoses, such as the Dynastab,

Fibulotape, Kallassy S, and the Kallassy were general perceived as more comfortable and stable in comparison to the semi-rigid orthoses (Malleoloc, Ligacast, Air Brace, Air Gel, Air Cast). However, the semi-rigid orthoses were perceived as easier to handle and less restrictive on performance.

2.11 The Biomechanics of Sprinting

The sprint gait cycle begins with foot-ground contact (initial contact) and ends when the same foot contacts the ground again. Stance phase begins at ground contact and ends when the foot leaves the ground. After the stance phase, toe-off marks the beginning of the swing phase, when the leg swings in front of the center of mass (Novacheck, 1998).

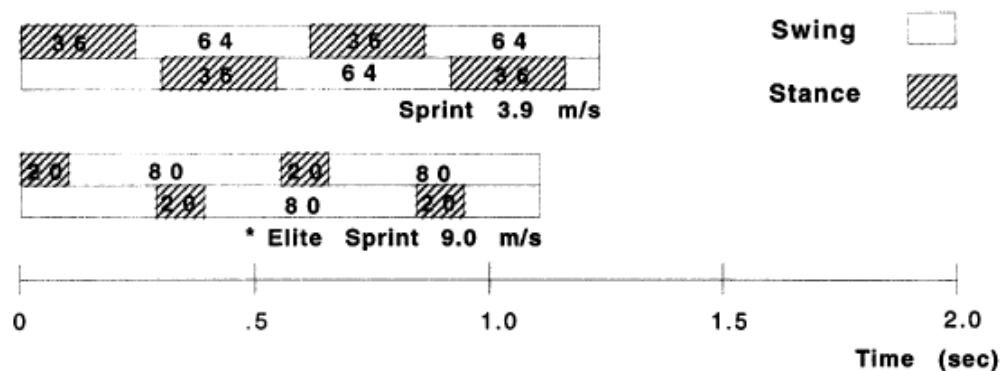


Figure 2.22. Comparison of stance and swing phase times between amateur and elite sprinters (Novacheck, 1998).

During sprinting, both feet are never in contact with the ground at the same time, unlike in walking. Both feet are airborne twice during a sprinting gait cycle, once at the beginning and once at the end of swing phase. These occurrences are referred to as double float. Toe-off timing depends on speed, with elite sprinters spending less time in contact with the ground (Figure 2.22) (Novacheck, 1998).

In sprinting, the body's center of gravity is lowest at ground contact due to greater hip flexion, knee flexion, and ankle dorsiflexion (Mann & Hagy, 1980). The pelvis and the trunk tilt further forward, and the center of gravity falls ahead of the contact point to facilitate forward acceleration. In sprinting, the initial contact is on the forefoot, unlike in walking and jogging where the initial contact is on the hindfoot (Novacheck, 1998). Sprinters are always on their toes (Mann & Hagy, 1980).

Core stability preservation is the first objective of sprinting mechanics. Focusing on core posture is essential to enhance stability. To achieve optimal core stability, a sprinter's head, neck, and spine should be neutrally aligned, and the pelvis should have a slight posterior tilt. This allows the sprinter to achieve an upright trunk, a levelled head, and maximal hip height during the push-off and swing phases. The muscles surrounding the spine should be strong enough to provide a stable basis for limb movement. Efficient sprinters demonstrate pelvic rotation that can increase stride length by up to five centimetres. This is a tremendous gain in performance over a 100 m course. Proper core stability promotes front side mechanics and limits backside mechanics. Front side mechanics occur in front of the body, such as leg swing; backside mechanics refer to actions occurring behind the body, such as the toe-off. Greater frontside mechanics and lesser backside mechanics enhance stability, minimize braking forces, and increase propulsive vertical forces, counteracting gravity and leading to increased momentum and improved sprinting efficiency (Young, 2006).

The second objective of efficient sprinting is minimizing braking forces that occur when the sprinter comes into contact with the ground. Braking forces from ground contact cause horizontal deceleration. Although braking forces are inevitable, their magnitude should be minimized because they affect the overall core stability of the athlete. The main cause of excessive braking forces is ground contact too far in front of the center of mass (under the athlete's pelvis) when attempting to increase stride length. Another cause of excessive braking forces occurs when the body attempts to regain stability by premature grounding of the swing leg (Young, 2006).

In conclusion, the sprinter must strive to preserve postural stability, minimize braking forces, and increase propulsive forces by running with optimal posture, increasing frontside mechanics, and minimizing backside mechanics (Young, 2006).

2.11.1 Sprinting gait phases

2.11.1.1 *Ground contact*

As mentioned above, ground contact should be made with the foot as close to directly beneath the centre of mass as possible to minimize braking forces and increase vertical force propulsion. At ground contact, both thighs should be in line, parallel with each other, and the tibia of the support leg should be somewhat perpendicular to the ground. These positions are observed with proper posture, with a slight posterior pelvic tilt (Young, 2006).

2.11.1.2 *Stance phase*

At the beginning of stance phase, the sprinter absorbs impact forces from ground contact. The foot in contact with the ground is called the support foot. During stance phase, the body travels over and in front of the support foot. The swing leg begins to travel forward and upward. The heel of the swing leg should remain tucked to the gluteal muscles. As the thigh of the swing leg moves in front of the body, the lower leg should begin to extend at the knee (Young, 2006).

2.11.1.3 *Toe-off/Pull-off*

At toe-off, the body should be in an upright position. Young (2006) claims that the “hip of the swing leg should be projected forward slightly and the knee should be high and in front of the body”. This swing-leg knee position stretches the hamstrings and gluteal muscles to increase their capacity for speed and force development, accelerating the thigh downward for subsequent ground contact. In this thesis, ‘pull-off’ was used for the cut movement since the lateral aspect of the participant’s foot was sometimes the last part to leave the ground.

2.11.1.4 *Flight phase*

Once the sprinter’s foot leaves the ground, the sprinter is in flight phase. After toe-off, the heel of the push-off foot should be brought up toward the buttocks. This action is due to aggressive hip flexion, not hamstring flexion (Young, 2006). The hamstrings are not contracted during flight phase (Mann & Hagy, 1980).

At the end of the flight phase, the ankle should be slightly dorsiflexed. Dorsiflexion will delay ground contact by a fraction of a second, leading the touchdown foot beneath the

centre of mass and considerably reducing braking forces (Young, 2006). In addition, a slightly dorsiflexed foot will increase the posterior leg muscle group stretch, which could produce faster downward acceleration of the thigh and lower leg, and greater force in the gastrocnemius complex. Increased foot speed could reduce braking forces at ground contact.

2.11.1.5 *Arm swing*

Arm swing counterbalances leg movements to stabilize trunk rotation (Mann & Herman, 1985) and enhances vertical propulsive forces (Young, 2006).

2.11.2 The roles of the hips, knees and ankles in sprinting

In sprinting, maximum posterior pelvic rotation occurs in midswing to lengthen the stride. However, at ground contact, the pelvis has already rotated anteriorly. Maximum hip extension occurs just before toe-off and maximum flexion occurs during mid-to-late swing phase. As sprint velocity increases, the maximum hip flexion also increases to allow for a longer step length. However, if the step is too far ahead of the center of mass, deceleration can occur due to the foot coming in contact with the ground too early (Novacheck, 1998).

Knee flexion increases with running speed, while knee extension decreases. In sprinting, the knee is flexed continuously, even in stance phase at an angle of approximately 20°. Knee flexion in sprinting varies between 105° (Novacheck, 1998) and 140° (Mann, R. A. & Hagy, J., 1980). Maximum knee extension occurs during propulsion, peaking at 20°.

The ankle dorsiflexes at ground contact through impact, but the heel never touches the ground. The ankle dorsiflexes as body weight is transferred to the stance leg (Novacheck,

1998). This dorsiflexion is quickly followed by rapid plantar-flexion (Mann, R. A. & Hagy, J., 1980). Plantar-flexion leads to pronation that relaxes the transverse tarsal joint to allow the foot to act as a shock absorber. Peak pronation normally occurs at 40% of stance phase, before the foot begins to supinate and reach a neutral position at 70% of stance phase (Novacheck, 1998).

2.11.3 Stride parameters

Stride parameters are typically used to characterize running and walking gait. These parameters include:

- Stride length (m): Distance between foot-strike and the next foot-strike from the same foot. By increasing stride length and stride frequency, a person can run faster. Stride length and stride frequency are interdependent; as one variable increases, the other decreases. Optimal balance between stride length and stride frequency must be achieved to run faster (Young, 2006).
- Cycle time (ms): Time recorded between foot-strike and the next foot-strike from that same foot. Hunter et al. (2004) describe cycle time as sprint velocity divided by step length.
- Velocity (m/s): Described by Churchill et al. (2003) as the average speed over one gait cycle (stride length/cycle time). For males, Mann & Hagy (1980) reported the mean sprinting velocity as 7.69 m/s and Hunter et al. (2005) reported sprint velocities between 7.44 and 8.80 m/s.

- Step length (m): Distance between foot-strike of one foot and the next foot-strike of the opposite foot, illustrated in Figure 2.23 (Hunter et al., 2004). Step lengths can be normalized by dividing absolute values by participant height, to allow for between-subject comparisons (Bezodis et al., 2008). Bezodis et al. (2008) recorded step lengths from 1.94-2.35 m.
- Step time (ms): Time between foot-strike of one foot and the next foot-strike of the other foot.
- Cadence (steps/minute): The number of steps per minute.

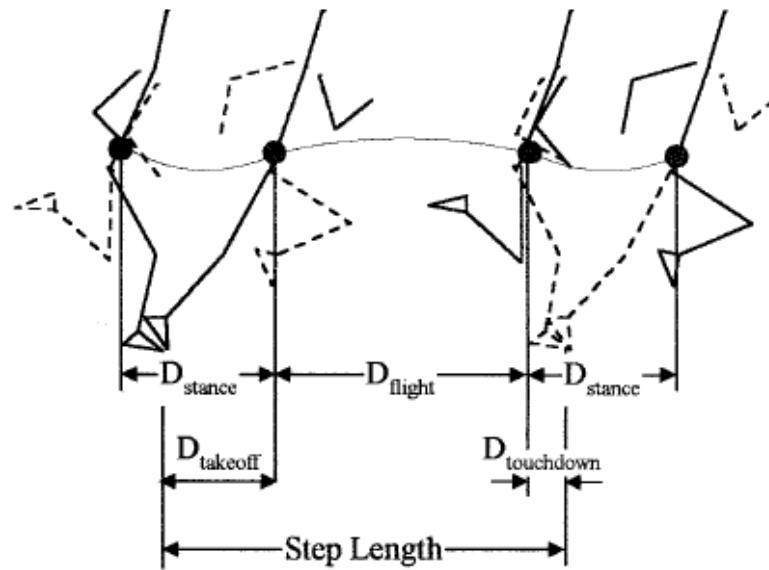


Figure 2.23. Step length in sprinting (Hunter et al., 2004).

- Stance time (ms): Described as the amount of time the foot was in contact with the ground (from foot-strike to toe-off) (Churchill et al., 2003). Stance phase is

approximately 22% of the gait cycle in sprinting (Figure 2.24) (Mann, R. A. & Hagy, J., 1980).

- Swing time (ms): The amount of time the non-stance leg spends moving forward (from toe-off to foot-strike) (Churchill et al., 2003).

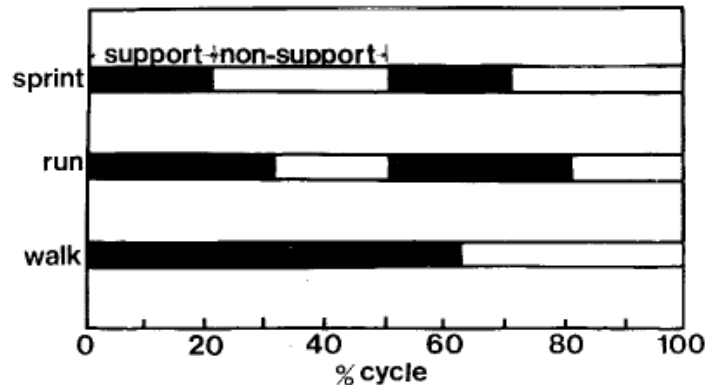


Figure 2.24. Percentage of support during walking, running, and sprinting (Mann & Hagy, 1980).

- Swing velocity (m/s): The average speed during the swing phase (stride length/swing time). Weyand et al. (2000) found that elite sprinters do not swing their limbs significantly faster through the air compared to amateur sprinters.
- Flight (ms): The time between toe-off of one foot and foot-strike of the opposite foot, also known as the period of non-support (Hunter et al., 2004). Elite sprinters spend less time on the ground because the forces they produce allow them to enter a period of flight more rapidly than less efficient sprinters (Mann & Herman, 1985).

2.12 The Biomechanics of Single-Legged Take-Off Jumping and Landing

In one-legged vertical jumping, the jumping phase is the time between maximum knee flexion angle and push-off, and the landing phase is the time between ground contact and maximum knee flexion. The dominant leg is defined as the push-off leg (Yu et al., 2006).

Ankle orthoses restrict motion in both the frontal and sagittal planes. Ankle restriction from an orthosis alters normal ankle motion during impact from jump-landing (DiStefano et al., 2008). The ASO orthosis restricted plantar-flexion at initial ground contact, maximum dorsiflexion, and total ankle joint displacement. However, DiStefano et al. (2008) observed an increase in knee flexion at initial ground contact.

Vertical jump height can be measured using the sacral marker and calculated as percent body height (Benjaminse et al., 2007). However, Van Soest et al. (1985) describe the jumping height as the vertical distance between the greater trochanter during a standing static trial and the highest point of the trochanter during a jump. Their results showed that the one-legged jump height was 58.5% of the two-legged jump height. On average, pre-fatigue heights for both one and two-legged jumps, for males and females, were 20.16% and 15.26% of their height, respectively. Post-fatigue, jump heights were 18.08% and 15.32% of their percent body height (Benjaminse et al., 2007).

2.13 The Biomechanics of Cutting

2.13.1 The sidestep cut

Cutting is a change in running path direction by planting one foot onto the ground and pushing off to start running in a different direction. To accelerate and decelerate efficiently, the cutter (person making the cut) must lean the trunk forward to keep the centre of gravity low. A low centre of gravity provides more stability, facilitating quicker changes of direction (Sheppard & Young, 2006). Stride length often shortens before making a change of direction (Sayers, 2000).

Deceleration occurs over several gait cycles and starts when the ankle of the front leg plantarflexes after foot-strike, enabling the whole foot to contact the ground (Figure 2.25). The torso becomes more upright and the quadriceps and gastrocnemius aid deceleration. Knee flexion occurs after dorsiflexion of the front leg so that the center of mass stays posterior to the planted foot (Andrews et al., 1977).

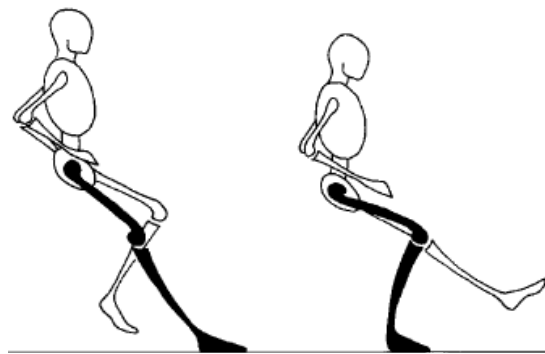


Figure 2.25. Preliminary deceleration phase (Andrews et al., 1977).

The last deceleration step is foot planting that initiates push-off into a different running direction. Before planting the foot, the pivot leg is slightly flexed at 60° and the foot is dorsiflexed. After planting the foot, the pivot foot pushes off, starting acceleration in the new direction. The hip and knee are extended and the ankle comes into full plantar-flexion (Figure 2.26, Figure 2.27) (Andrews et al., 1977; Dayakidis & Boudolos, 2006). The torso rotates fully toward the new direction, positioning the swing leg in that same direction. The swing leg provides acceleration in the direction the participant intends to go. Lowering the center of gravity causes the hips to be more flexed in comparison to normal running conditions (Andrews et al., 1977).

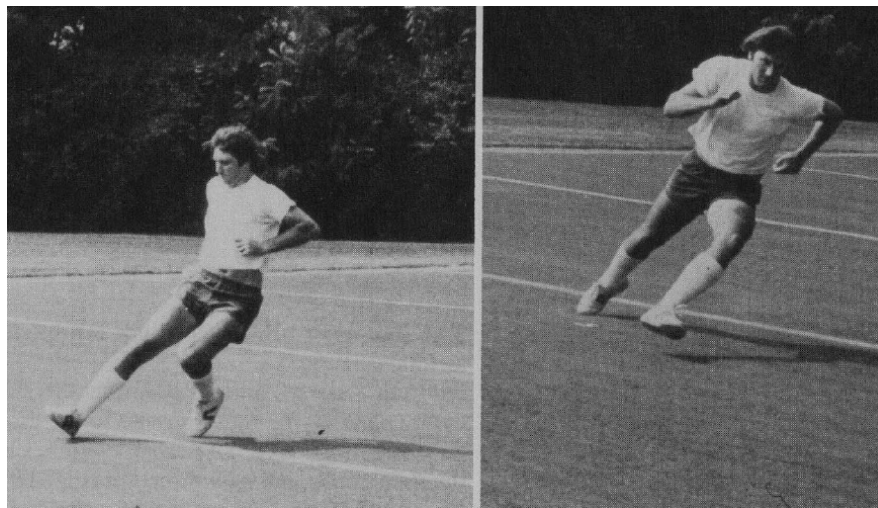


Figure 2.26. The sidestep cut (Andrews et al., 1977).

2.13.2 The influence of the ASO orthosis on stance phase during cutting

Gudibanda & Wang (2005) defined the stance phase of cutting to be divided as the following: the first 25% is early stance, 26%-75% is midstance, and 76%-100% is late

stance. In early stance, the ASO significantly decreased peak inversion and plantar-flexion. In mid and late stance, the ASO significantly decreased peak inversion. By restricting plantar-flexion and inversion in early stance phase, the ASO may prevent ankle sprains. However, ankle inversion-eversion and plantar-dorsiflexion angular velocities in early and late stance phases were not hindered by the ASO (Gudibanda & Wang, 2005).

The ASO significantly decreased the maximum plantar-flexion angle by 48% in forward lateral cutting. However, the participants were nonathletes, had uninjured ankles, and performed cuts without shoes (Gudibanda & Wang, 2005).

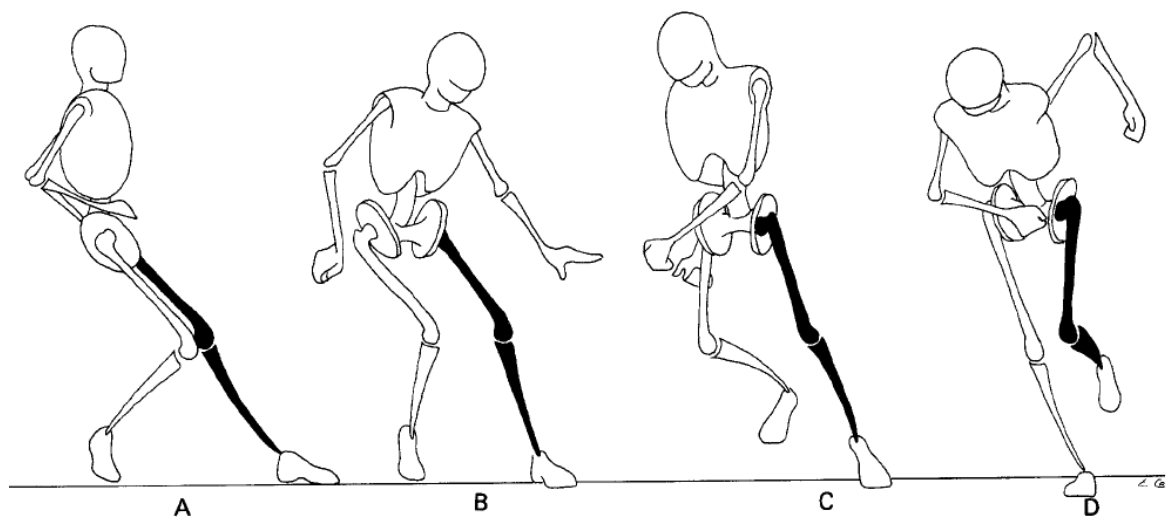


Figure 2.27. The sidestep cut: A) deceleration, B) plant, C) rotate and push-off, D) run in different direction (Andrews et al., 1977).

2.14 Summary of gaps in literature

Orthoses are worn to help protect the ligaments of the ankle, and subsequently prevent ankle injuries. Both lace-up and SRS orthoses support the ankle during exercise (Jerosch et

al., 1995). Individuals with moderate to severe ankle injuries are encouraged to wear an ankle orthosis during physical activity for at least six months following the injury (Thacker et al., 1999). Wearing an orthosis during the rehabilitation stage encourages individuals to participate in sport.

The literature demonstrates that SRS orthoses prevent ankle injuries (Pedowitz's, 2008) without hindering performance (Gross & Liu's, 2003). SRSs do not enhance proprioception (Kernozek et al., 2008), but they restrict passive inversion before and after exercise (Gross et al., 1994), and reduce jump height (Verbugge, 1996). However, in Greene & Wight's (1990) study, the SRS orthosis was the only orthosis to improve running time around the bases of a baseball diamond. Participants in other studies found that SRS orthoses provided excellent support and comfort (Beriau et al., 1994; Verbugge's, 1996).

The lace-up orthosis also significantly reduced jump height (Paris, 1992); however, this orthosis type significantly reduced reoccurrences of ankle injuries (Sharpe et al., 1997). Performance differences in sprinting, jumping and cutting were insignificant between the SRS and the lace-up orthoses (Rosenbaum et al., 2005). However, the participants perceived SRS orthoses, including the Malleoloc, to be significantly easier to handle and provide more support; and lace-up orthoses to be more comfortable and allow less performance restriction (Alves et al., 1992; Beriau et al., 1994; Rosenbaum et al., 2005). Lace-up orthoses were perceived to be less restrictive for speed and quickness compared to SRS orthoses. On the contrary, in other studies, participants preferred the SRSs to the lace-up orthoses (Alves et al., 1992; Greene & Wight's, 1990).

ASO orthoses can be worn on both ankles, with or without shoes. The figure-8 strap can be tightened without removing the shoe. The purpose of the ASO is to reduce inversion and eversion injuries/re-injuries (Achilles Medical, 2008). In sideward lateral cutting, the ASO significantly decreased the peak plantar-flexion angle by 41% in early stance. In forward lateral cutting, the ASO significantly decreased the plantar-flexion angle by 48% in early stance, and peak inversion angle during mid and late stance phases. Out of 10, participants gave the ASO 7.9 (1.1) for comfort, 7.4 (1.8) for ease of application, 8.1 (1.2) for level of support, and 7.4 (1.1) for effect on performance in a study where participants wore the orthosis without shoes. There were no significant differences in angular velocities (Gudibanda & Wang, 2005). In another study, the ASO restricted plantar-flexion at initial ground contact and maximum dorsiflexion in jump-landing, as well as total ankle joint displacement (DiStefano et al., 2008).

The Malleoloc SRS orthosis is only worn with footwear and is designed to counteract supination and lateral twisting of the ankle (Bauerfeind USA Inc., 2008). Research with the Malleoloc reported significantly less passive eversion and plantar-flexion than those with soft orthoses (Eils et al., 2002). In addition, the Malleoloc helped quicken pronation during the single-leg jump, compared to no orthosis (Jerosch et al., 1997), but did not have a significant effect on jumping and figure-8 test performances (Wiley & Nigg, 1996).

ROM restrictions imposed by both lace-up and SRS orthoses might interfere with the biomechanics of sprinting, one-legged jumping and cutting, as the lower-limb moves in a chain of reactions, starting with ground contact. In sprinting, increased dorsiflexion occurs

once the ball of the foot contacts the ground (Mann & Hagy, 1980). In one-legged jumping, the ankle dorsiflexes at ground contact as body weight is transferred to the stance leg (Novacheck, 1998), before rapid plantar-flexion (Mann & Hagy, 1980). Plantar-flexion leads to pronation that relaxes the transverse tarsal joint to allow the foot to act as a shock absorber.

In cutting, deceleration starts when the ankle of the front leg plantarflexes after foot-strike, causing the whole foot to contact the ground. The torso becomes more upright and the quadriceps and gastrocnemius aid deceleration. Before planting the foot, the pivot leg flexes slightly and the foot dorsiflexes. After planting the foot, the pivot foot pushes off into a new direction, plantarflexing the ankle (Andrews et al., 1977; Dayakidis & Boudolos, 2006).

Previous ASO testing by Gudibanda & Wang (2005) had non-athletic participants performing movements without shoes, which is different from a real activity setting. This thesis evaluated the ASO with running shoes to allow natural movement. In addition, orthosis effects on the different gait phases for sprinting, one-legged jumping and 45-degree cutting were evaluated, since there is little research across all three movements in this domain. There is no statistically significant research on perceived levels of comfort and ankle support between the ASO and Malleoloc orthoses.

Chapter 3: Methods

3.1 Participants

A convenience sample of 13 adult Ultimate players (20-39 years of age) was recruited from the Ottawa Ultimate community (Table 2, Table 3). Body Mass Index (BMI) results for each participants may vary from one testing session to the other due to loss of weight throughout the Ultimate season, or an increase in muscle mass. Recruited participants wore an ankle orthosis during activity on a regular basis. Most participants wore an ankle orthosis because of past ankle sprains, for added security and to prevent re-injury. Eleven of the thirteen participants had been wearing an orthosis for a minimum of one year prior to testing; and nine of the thirteen participants had been wearing an orthosis for over two years. Participants had a minimum of one year of experience playing competitive Ultimate. They participated in a minimum of two exercise sessions per week during the time of their testing, such as an Ultimate session or a sprint-training session. Testing occurred throughout the competitive Ultimate season, therefore, most participants had a two-and-a-half-hour practice twice per week and a tournament every second weekend. Participants did not have a lower-body injury that prevented them from participating in their regular exercise, for a minimum of a week, within the six months prior to testing.

All participants read an information letter (Appendix A: Recruitment Letter) and consent form (Appendix B: Consent Form) describing the study details. On the testing day,

the study details were reviewed with the participant who signed a consent form before the testing.

Table 2. *Male participant characteristics (standard deviation in brackets). BMI results are for the two test days.*

Participant	Age	Height (m)	Mass (kg) ASO trials	Mass (kg) Malleoloc trials	BMI (kg/m ²)
2-5	33	1.78	76.6	76.3	24.3, 24.2
2-8	37	1.83	78.0	77.3	23.3, 23.1
2-9	29	1.78	82.8	83.5	26.3, 26.5
Average	33 (4)	1.79 (0.03)	79.13 (3.29)	79.01 (3.94)	24.6 (1.53) 24.6 (1.73)

Table 3. *Female participant characteristics (standard deviation in brackets). BMI results are for the two test days.*

Participant	Age (years)	Height (m)	Mass (kg) ASO trials	Mass (kg) Malleoloc trials	BMI (kg/m ²)
2-2	22	1.55	53.3	54.1	22.2, 22.5
2-4	20	1.58	52.1	57.3	21.0, 23.1
2-6	36	1.60	62.1	62.4	24.2, 24.4
2-7	20	1.58	52.7	52.8	21.3, 21.3
2-10	23	1.78	66.6	66.7	21.2, 21.2
2-11	36	1.78	68.5	68.9	21.7, 21.9
2-12	39	1.65	70.7	70.7	26.0, 26.0
2-13	20	1.68	59.4	61.1	21.2, 21.8
2-14	27	1.68	68.6	66.4	24.5, 23.7
2-15	37	1.70	68.6	68.6	23.7, 23.8
Averages	28 (8.1)	1.66 (0.08)	62.26 (7.41)	62.9 (6.41)	22.7 (1.76), 22.97 (1.53)

3.2 Equipment

All data were collected in a motion analysis laboratory on a tile floor. Lower-limb kinematic data was collected using a seven camera (MX3s) Vicon Motion Capture system, recording at 100 Hz. Vicon is a highly accurate motion tracking system with an estimated translation error of 0.3 mm and an estimated axial rotation error of 0.06 degrees (McNamara

et al., 2009). Cameras were placed at a maximum of eight metres from the center of the capturing volume. System calibration was performed every testing day.

Participants had 38, 14 mm reflective markers taped to specific anatomical landmarks of their lower-body, using double-sided, hypoallergenic tape. These landmarks make up the Six Degree of Freedom (6DoF) marker set (Appendix E: Marker Set), and include the anterior superior iliac spines, iliac crests, posterior superior iliac spines, greater trochanters. In addition, there are four-marker clusters on each thigh, lateral and medial condyles, four-marker clusters on each shank, lateral and medial malleoli, right and left heel, and first and fifth metatarsal heads of each foot. The 6DoF marker set is established and frequently used in the field of biomechanics (Collins et al., 2009; Schmitz, 2008) and is not susceptible to errors in ankle and knee rotation during deeper knee flexion and knee movements out of the sagittal plane, as experienced with models such as Plug-in-gait. The chosen marker configuration increases marker and segment visibility during various movements. Participants wore appropriate indoor running shoes and tight-fitting clothes with no reflective material to minimize marker movement over the skin.

3.3 Procedure

3.3.1 Testing overview

Testing took place in the Rehabilitation Technology Laboratory at the Ottawa Hospital Rehabilitation Centre. Participants completed two testing sessions, one with a new ASO orthosis and another with a new Malleoloc orthosis (Table 4). Both orthosis models were

fitted to each participant's foot/feet according to manufacturer's specifications. Nine of thirteen participants wore orthoses on both feet during activity, and the other four participants only wore an orthosis on their right foot. Participants were randomly assigned to the ASO or Malleoloc group. Participants wore each orthosis, while performing their typical physical activities, for a minimum of three weeks prior to testing to allow their body to adapt to the changes imposed by the orthosis, and for the orthosis to conform to the participant's ankle(s) and foot/feet. An acclimatization of 2-4 weeks is recommended when trying a new orthosis (Turner & Merriman, 2005). After testing with one orthosis model, participants wore the other orthosis model for a minimum of three weeks before participating in session two. The only difference between sessions one and two was the orthosis model worn by the participant.

Table 4. *ASO and Malleoloc orthosis product details.*

ASO	Malleoloc
• Lace-up sleeve • Made of ballistic nylon with two opposing non-stretch stabilizing figure-8 straps that attach at the medial and lateral aspects of the shank • Elastic cuff closure at the bottom of the shank covers the laces, the figure-8 straps, and secures the orthosis to the leg • Can be tightened without being removed from the shoe • Can be worn on right or left ankles • Can be worn with or without shoes (Achilles Medical, 2008)	• Flexible polypropylene stirrup, cushioned with a thin layer of foam-like material. (Bauerfeind USA Inc., 2008) • Can be worn inside shoes or cleats • Two straps, one on the lower shank above the ankle and one in a 'figure-8' around the ankle (Baier & Hopf, 1998)

3.3.2 Testing session agenda

Upon arrival for the first testing session, participants signed a consent form (Appendix B: Consent Form) and completed Part A of a short questionnaire (Appendix C: Ankle Orthosis Questionnaire). This questionnaire was based on an orthosis evaluation questionnaire by Bauerfeind, but included additional questions on ankle orthosis function and satisfaction. The questionnaire contained questions about the participant's ankle injury, the orthosis they were wearing at the time of the testing, and the orthosis comfort and function during exercise. Subsequently, participants changed into their body-fitted testing clothes, and anthropometric information was recorded on the participant evaluation form (Appendix D: Subject Data Sheet). Afterwards, the research assistant evaluated ankle ROM with a goniometer.

Participants performed three trials of one-legged jumping and cutting, and five trials of sprinting to ensure a minimum of three trials with right-foot ground contact were captured, for a total of 11 trials per testing session. Testing was performed in a motion analysis laboratory with a capture volume of 5m x 6m. Sprinting consisted of running at maximum speed on a 14-meter runway, with the capture volume in the middle of the runway. The one-legged jump started with a nine-meter sprint to a maximal right-leg vertical push-off jump in the middle of the capture volume. The cutting manoeuvre consisted of a five-meter run before planting the right foot on a marked area in the capture volume and running along a path 45 degrees from the initial running path. The outline of the 45-degree cut was taped on the floor. Cutting trials that veered from the 45-degree cutting line were excluded and the

trial was repeated to ensure that participants were making a 45-degree cut. The activity testing order for each subject was randomized.

Following testing, participants completed Part B of the questionnaire (Appendix C: Ankle Orthosis Questionnaire), asking about ankle laxity, ankle orthosis details and perceived ROM, comfort, confidence, and stability during testing.

3.4 Data Processing and Statistical Analysis

All participants were right-foot dominant and wore an orthosis on their right ankle; therefore, only right foot data were analyzed. The Vicon Nexus software was used to fill gaps in marker trajectories before exporting the data to Visual3D (C-Motion, 2013). In Visual3D, four gait event codes were identified in each trial: five frames before foot-strike, foot-strike, foot-off, five frames after foot-off, and marker trajectories were filtered with a 10 Hz dual-pass Butterworth filter. A 6 DoF model was used to compute right ankle angles and angular velocities in the sagittal and frontal planes. Each trial was normalized to 100% of stance, and all ankle kinematic data were exported to Microsoft Excel for extraction of maxima and minima from each trial. These values were then averaged to create one data set for each participant. Paired t-tests with and without a Bonferroni correction were used to compare peak values between the ASO and Malleoloc conditions. Effect sizes were obtained with Cohen's *d*.

Stance times were extracted from each movement, and one-legged jump height. Paired t-test were used to compare results of the ASO and Malleoloc orthoses.

Questionnaire data was also collected to determine perceived comfort, stability and confidence when wearing the orthoses, with ratings from poor to excellent. A Mann-Whitney-Wilcoxon test was used to compare the non-parametric data from the ASO and Malleoloc questionnaires of each participant, and effect sizes (r) were obtained for each comparison.

Chapter 4: Results

4.1 Kinematic Results

4.1.1 Cut

As shown in Table 5, the ASO peak plantar-flexion angle during weight acceptance was significantly greater compared to the Malleoloc ($p = 0.038$, $d = 0.553$, power = 13.6%, $\alpha = 0.05$, two-tail). This result would be insignificant with a Bonferroni corrected p value of 0.0028. ASO angle averages for peak plantar-flexion during pull-off, plantar-flexion to dorsiflexion range (foot-strike to midstance), and dorsiflexion to plantar-flexion range (midstance to pull-off) were all greater than the Malleoloc, except for peak dorsiflexion during midstance which was slightly less with the ASO. However, these angles were not significantly different between the orthosis groups for the cut ($p > 0.05$).

Table 5. *Average dorsiflexion (DF) and plantar-flexion (PF) angle (deg) and angular velocity (AV, deg/s) maxima and minima for the cutting activity (standard deviation in brackets).*

Gait Events	ASO	Malleoloc	p	d
PF angle during weight acceptance	-12.83 (8.29)	-7.51 (10.79)	0.038	0.553
DF angle during midstance	27.25 (12.93)	28.88 (5.89)	0.550	0.162
PF angle during pull-off	-22.11 (7.42)	-18.33 (6.74)	0.095	0.533
PF to DF angle range (foot-strike to midstance)	40.08 (8.70)	36.38 (10.63)	0.365	0.381
DF to PF angle range (midstance to pull-off)	49.36 (11.78)	47.20 (6.19)	0.542	0.23
DF angular velocity after foot-strike	439.16 (140.17)	513.27 (133.11)	0.167	0.542
PF AV during midstance	-493.35 (89.37)	-471.99 (144.93)	0.637	0.177
PF AV during pull-off	128.53 (40.46)	113.3 (57.34)	0.405	0.307
DF to PF AV range (midstance)	932.51 (197.64)	985.26 (235.24)	0.536	0.243
PF AV range (midstance to pull-off)	621.87 (109.89)	585.29 (166.62)	0.472	0.259

Plantar and dorsiflexion angular velocities for each outcome of the cut were not significantly different between the ASO and Malleoloc groups ($p>0.05$).

In Table 6, the eversion-to-inversion angle range from weight acceptance to midstance, and inversion-to-eversion angle range from midstance to toe-off were greater with the ASO, but not significant ($p>0.05$). Peak inversion angle during midstance was close to statistical significance ($p = 0.059$, $d = 0.5$, power = 11.9%, alpha = 0.05, two-tail). This result would be insignificant with a Bonferroni corrected p value of 0.0028. The angle averages for eversion during weight acceptance and eversion during toe-off were greater with the Malleoloc, but these results were not significant ($p>0.05$). The peak eversion angles during toe-off were very similar between the ASO and the Malleoloc (difference in averages of 0.21 deg).

Table 6. Average ankle inversion and eversion angle (deg) and angular velocity (AV, deg/s) maxima and minima for the cutting activity (standard deviation in brackets).

Gait Events	ASO	Malleoloc	<i>p</i>	<i>d</i>
Eversion angle during weight acceptance	3.46 (3.98)	5.71 (4.97)	0.059	0.5
Inversion angle during midstance	47.76 (7.45)	45.85 (4.91)	0.405	0.303
Eversion angle during toe-off	14.57 (3.80)	14.78 (2.46)	0.889	0.07
Eversion-to-inversion angle range (weight acceptance to midstance)	44.30 (6.46)	40.14 (8.13)	0.093	0.57
Inversion-to-eversion angle range (midstance to toe-off)	33.19 (8.12)	31.07 (5.08)	0.467	0.313
Inversion AV after ground contact	785.98 (168.80)	686.72 (247.07)	0.207	0.469
Eversion AV before toe-off	-428.99 (119.82)	-425.11 (51.37)	0.925	0.042
Inversion-to-eversion AV range (ground contact to toe-off)	1214.97 (200.90)	1111.83 (282.73)	0.310	0.421

Peak angular velocities for inversion after ground contact, eversion in preparation for toe-off, and inversion-to-eversion range from ground contact to toe-off were all greater with

the ASO in comparison to the Malleoloc. The ASO inversion-to-eversion angular velocity was almost 100 deg/s more than the Malleoloc from ground contact to toe-off. However, no inversion and eversion angular velocity differences were significant for the cut ($p>0.05$).

Table 7. *Average dorsiflexion (DF) and plantar-flexion (PF) angle (deg) and angular velocity (AV, deg/s) maxima and minima for the jump activity (standard deviation in brackets).*

Gait Events	ASO	Malleoloc	<i>p</i>	<i>d</i>
DF angle prior to foot-strike	13.32 (8.25)	12.93 (6.92)	0.797	0.051
PF angle during midstance	-14.89 (3.98)	-14.48 (5.26)	0.789	0.088
DF angle during midstance	9.53 (4.45)	10.54 (4.59)	0.569	0.223
PF angle during pull-off	-34.15 (3.49)	-33.74 (5.77)	0.787	0.086
DF to PF angle range (foot-strike to midstance)	28.21 (8.79)	27.41 (5.05)	0.702	0.112
PF to DF angle range (midstance)	24.41 (4.56)	25.02 (2.89)	0.649	0.16
DF to PF angle range (midstance to pull-off)	43.67 (4.73)	44.28 (4.6)	0.683	0.131
DF AV before foot-strike	-53.94 (64.47)	-33.68 (98.94)	0.344	0.243
PF AV after foot-strike	-567.71 (248.47)	-583.93 (291.80)	0.855	0.06
DF AV during midstance	427.87 (60.21)	427.26 (60.96)	0.977	0.01
PF AV during midstance	-734.86 (68.32)	-745.09 (53.27)	0.700	0.167
PF AV during pull-off	-19.43 (44.62)	-17.28 (48.52)	0.873	0.046
DF to PF AV range (preparation for foot-strike to weight acceptance)	513.77 (303.57)	550.25 (325.70)	0.700	0.116
PF to DF angular velocity range (weight acceptance to midstance)	995.58 (255.93)	1011.19 (321.89)	0.867	0.054
DF to PF AV range (midstance)	1162.73 (108.11)	1172.35 (74.48)	0.821	0.104
PF AV range (midstance to pull-off)	715.43 (98.74)	727.81 (55.59)	0.647	0.155

4.1.2 Jump

In Table 7, no significant differences in plantar-flexion and dorsiflexion angle averages were found between the ASO and Malleoloc when performing the one-legged jump ($p>0.05$). Peak angles for dorsiflexion prior to foot-strike, plantar-flexion during midstance, plantar-flexion during pull-off, and dorsiflexion to plantar-flexion range from foot-strike to midstance were less than one degree greater with the ASO. Peak angles for dorsiflexion

during midstance (more than one degree), plantar-flexion to dorsiflexion range during midstance, and dorsiflexion to plantar-flexion range from midstance to pull-off were greater with the Malleoloc, but by less than one degree. For the jump, all average angle outcomes for both ASO and Malleoloc groups were very similar, and therefore, no statistically significant differences were found ($p>0.05$).

ASO plantar-flexion angular velocities after foot-strike and during pull-off were greater compared with the Malleoloc. Dorsiflexion angular velocity during midstance was similar between the ASO and the Malleoloc (difference in averages of 0.61 deg). Angular velocities at plantar-flexion after foot-strike, plantar-flexion during midstance, dorsiflexion to plantar-flexion range from preparation for foot-strike to weight acceptance, plantar-flexion to dorsiflexion range from weight acceptance to midstance, dorsiflexion to plantar-flexion range during midstance, and plantar-flexion range from midstance to pull-off were greater with the Malleoloc. However, no plantar and dorsiflexion angular velocity outcomes were significantly different between the ASO and the Malleoloc groups ($p>0.05$).

In Table 8, Malleoloc ankle angles were greater in comparison to the ASO for eversion after foot-strike, inversion in preparation for toe-off, inversion-to-eversion range pre-to-post foot-strike, and eversion-to-inversion range during stance phase. Eversion-to-inversion range during stance phase was significantly greater with the Malleoloc in comparison to the ASO ($p = 0.048$, $d = 0.694$, power = 19.1%, alpha = 0.05, two-tail). This result would be insignificant with a Bonferroni corrected p value of 0.0019. All other ankle angle inversion and eversion outcome differences were not statistically significant for the

one-legged jump ($p>0.05$). Inversion angle in preparation for foot-strike, and inversion-to-eversion range pre-to-post toe-off were similar between the ASO and Malleoloc groups, with the ASO recording greater angle averages only by 0.31 deg and 0.4 deg, respectively. These minute differences were not statistically significant ($p>0.05$).

Table 8. *Average ankle inversion and eversion angles (deg) and angular velocity (AV, deg/s) maxima and minima for the jump activity (standard deviation in brackets).*

Gait Events	ASO	Malleoloc	<i>p</i>	<i>d</i>
Inversion angle in preparation for foot-strike	9.16 (5.97)	8.85 (3.80)	0.879	0.062
Eversion angle after foot-strike	-8.57 (4.31)	-10.06 (4.94)	0.160	0.321
Inversion angle in preparation for toe-off	-0.11 (3.72)	1.42 (4.12)	0.286	0.39
Eversion angle during pull-off	-5.04 (4.69)	-3.11 (4.36)	0.328	0.426
Inversion-to-eversion angle range (pre-to post-foot-strike)	17.73 (4.87)	18.91 (4.24)	0.465	0.258
Eversion-to-inversion angle range during stance phase	8.46 (2.41)	11.48 (5.66)	0.048	0.694
Inversion-to-eversion angle range (pre-to-post toe-off)	4.93 (3.72)	4.53 (2.60)	0.718	0.125
Inversion AV after foot-strike	-377.43 (108.33)	-397.08 (147.42)	0.694	0.152
Eversion AV during midstance	131.38 (32.19)	173.00 (83.98)	0.119	0.654
Inversion AV in preparation for toe-off	-99.54 (85.78)	-120.54 (82.12)	0.357	0.25
Inversion-to-eversion AV range (weight acceptance to midstance)	508.81 (128.50)	570.08 (171.45)	0.248	0.404
Eversion-to-inversion AV range (midstance to toe-off)	230.92 (91.82)	293.54 (120.31)	0.026	0.585

For the jump, all inversion and eversion angular velocity outcomes were greater with the Malleoloc compared to the ASO: inversion after foot-strike, eversion during midstance, inversion in preparation for toe-off, inversion-to-eversion range from weight acceptance to midstance, and eversion-to-inversion range from midstance to toe-off. However, only the Malleoloc eversion-to-inversion angular velocity range from midstance to toe-off was

significantly greater for the jump ($p = 0.026$, $d = 0.585$, power = 14.8%, alpha = 0.05, two-tail). This result would be insignificant with a Bonferroni corrected p value of 0.0019.

Table 9. *Average one-legged jump height (m) when wearing the ASO and Malleoloc orthoses (standard deviation in brackets). Participant 3 had one successful trial, therefore, standard deviation was not reported.*

Participant	ASO	Malleoloc
1	1.22 (0.044)	1.22 (0.005)
2	1.34 (0.003)	1.34 (0.016)
3	1.32	1.34 (0.015)
4	1.29 (0.011)	1.27 (0.011)
5	1.24 (0.024)	1.29 (0.014)
6	1.48 (0.036)	1.42 (0.032)
7	1.40 (0.032)	1.50 (0.035)
8	1.43 (0.032)	1.33 (0.037)
9	1.46 (0.010)	1.45 (0.029)
10	1.28 (0.014)	1.32 (0.021)
11	1.33 (0.033)	1.37 (0.026)
12	1.35 (0.019)	1.33 (0.007)
13	1.25 (0.038)	1.27 (0.03)
Average	1.34 (0.022)	1.34 (0.021)

The average one-legged jump height was calculated for each participant and orthosis using the pelvis segment vertical position, relative to the laboratory (Table 9). No significant difference was found between orthoses ($p = 0.74$). The average difference in jump height between orthoses was 0.04 m (SD = 0.03).

4.1.3 Sprint

The sprint plantar and dorsiflexion angle averages for the ASO and the Malleoloc were similar, but all angle averages were greater with the ASO, although not significantly different ($p > 0.05$). Dorsiflexion angle during midstance was only greater by 0.92 deg with the ASO compared to the Malleoloc (Table 10).

Plantar and dorsiflexion angular velocity outcomes were similar between the ASO and the Malleoloc. There were no significant differences ($p>0.05$).

Table 10. *Average dorsiflexion (DF) and plantar-flexion (PF) angle (deg) and angular velocity (AV, deg/s) maxima and minima for the sprint activity (standard deviation in brackets).*

Gait Events	ASO	Malleoloc	<i>p</i>	<i>d</i>
PF angle during weight acceptance	−4.39 (12.03)	−3.07 (10.83)	0.470	0.115
DF angle during midstance	25.73 (5.41)	24.81 (4.52)	0.469	0.185
PF angle during pull-off	−23.19 (10.58)	−21.85 (7.13)	0.549	0.149
PF to DF angle range (weight acceptance to midstance)	30.12 (8.33)	27.21 (7.62)	0.136	0.365
DF to PF angle range (from midstance to pull-off)	48.92 (11.4)	46.61 (6.27)	0.333	0.251
DF AV during midstance	560.41 (138.16)	565.88 (216.48)	0.920	0.03
PF AV during toe-off	−864.96 (131.25)	−856.19 (88.94)	0.790	0.078
DF to PF AV range (midstance to toe-off)	1425.37 (150.63)	1422.07 (207.88)	0.950	0.018

Table 11. *Average ankle inversion and eversion angle (deg) and angular velocity (AV, deg/s) maxima and minima for the sprint activity (standard deviation in brackets).*

Gait Events	ASO	Malleoloc	<i>p</i>	<i>d</i>
Inversion angle in preparation for foot-strike	10.68 (6.07)	11.01 (6.30)	0.843	0.053
Eversion angle after foot-strike	−2.68 (3.78)	−4.38 (6.47)	0.362	0.321
Inversion angle in preparation for toe-off	14.87 (5.12)	14.46 (5.64)	0.815	0.076
Eversion angle during pull-off	1.48 (4.15)	1.12 (2.91)	0.763	0.1
Inversion-to-eversion angle range (pre- to post-foot-strike)	13.36 (5.76)	15.39 (6.32)	0.341	0.336
Eversion-to-inversion angle range (stance phase)	17.54 (2.71)	18.85 (4.15)	0.387	0.374
Inversion-to-eversion angle range (pull-off)	13.39 (5.72)	13.23 (4.88)	0.932	0.03
Inversion AV after foot-strike	−344.44 (151.74)	−350.11 (159.32)	0.933	0.036
Eversion AV during midstance	234.44 (42.39)	269.34 (69.95)	0.161	0.603
Inversion AV (before toe-off)	−364.64 (154.01)	−338.96 (102.66)	0.612	0.196
Inversion-to-eversion AV range (weight acceptance to midstance)	578.88 (173.19)	605.79 (203.02)	0.726	0.143
Eversion-to-inversion AV range (midstance to toe-off)	599.07 (154.68)	620.48 (125.56)	0.933	0.152

In Table 11, inversion and eversion angle averages were similar between ASO and Malleoloc groups. There was less than one degree of difference between groups for the following outcomes: inversion in preparation for foot-strike, inversion in preparation for toe-off, eversion during pull-off, and inversion-to-eversion range during toe-off.

The following sprint inversion and eversion angular velocity outcomes were greater with the Malleoloc: inversion after foot-strike, eversion during midstance, inversion-to-eversion range from weight acceptance to midstance, and eversion-to-inversion range from midstance to toe-off were greater with the Malleoloc. No sprint angular velocity averages were significantly different between ASO and Malleoloc groups.

4.2 Stance Time

Due to the quickness of the activities and the small capturing volume (5m x 6m), stance time was the only relevant stride parameter available to analyze (Table 12). With the ASO, stance time ranged from 0.30 to 0.55 (s) for cutting, 0.20 to 0.27 (s) for jumping, and 0.13 to 0.19 (s) for sprinting. The Malleoloc's ranges were 0.29 to 0.52 (s) for cutting, 0.20 to 0.27 (s) for jumping, and 0.14 to 0.22 (s) for sprinting. No differences between the ASO and the Malleoloc were significant.

Table 12. *Average stance time (s) for ASO and Malleoloc for cutting, one-legged jumping and sprinting (standard deviation in brackets).*

Participant	ASO Cut	Malleoloc Cut	ASO Jump	Malleoloc Jump	ASO Sprint	Malleoloc Sprint
1	0.39 (0.05)	0.42 (0.05)	0.20 (0.02)	0.20 (0.01)	0.17 (0.02)	0.20 (0.02)
2	0.30 (0.03)	0.29 (0.09)	0.20 (0.02)	0.20 (0.02)	0.13 (0.01)	0.14 (0.01)
3	0.40 (0.06)	0.38 (0.06)	0.21 (0.01)	0.24 (0.02)	0.19 (0.06)	0.20 (0.01)
4	0.40 (0.08)	0.44 (0.02)	0.23 (0.06)	0.21 (0.06)	0.14 (0.01)	0.14 (0.01)
5	0.36 (0.06)	0.35 (0.11)	0.21 (0.02)	0.22 (0.03)	0.18 (0.06)	0.18 (0.02)
6	0.51 (0.08)	0.49 (0.04)	0.23 (0.02)	0.24 (0.06)	0.18 (0.01)	0.20 (0.00)
7	0.47 (0.09)	0.52 (0.09)	0.25 (0.06)	0.28 (0.01)	0.17 (0.06)	0.16 (0.06)
8	0.50 (0.08)	0.52 (0.07)	0.24 (0.01)	0.24 (0.01)	0.17 (1.00)	0.22 (0.01)
9	0.52 (0.06)	0.51 (0.11)	0.26 (0.02)	0.27 (0.06)	0.18 (0.06)	0.19 (0.03)
10	0.55 (0.04)	0.44 (0.02)	0.22 (0.02)	0.24 (0.02)	0.19 (0.06)	0.20 (0.01)
11	0.33 (0.01)	0.34 (0.02)	0.24 (0.02)	0.26 (0.01)	0.18 (0.01)	0.18 (0.01)
12	0.41 (0.03)	0.35 (0.04)	0.25 (0.01)	0.23 (0.02)	0.18 (0.06)	0.17 (0.01)
13	0.54 (0.09)	0.51 (0.09)	0.27 (0.01)	0.27 (0.01)	0.18 (0.01)	0.18 (0.01)
Average	0.44 (0.08)	0.43 (0.08)	0.23 (0.02)	0.24 (0.03)	0.17 (0.02)	0.18 (0.02)

4.3 Questionnaire Data

As shown in Figure 4.1, participants preferred the ASO to the Malleoloc when asked about overall satisfaction ($p = 0.003$, $r = 0.833$), fit inside the shoe ($p = 0.003$, $r = 0.833$), fit to foot when walking ($p = 0.002$, $r = 0.862$), and fit to foot when standing ($p = 0.002$, $r = 0.871$). Participants also significantly preferred the ASO when asked about their satisfaction

when wearing the orthosis for ankle range of motion (twisting) ($p = 0.010$, $r = 0.711$), comfort of the material ($p = 0.002$, $r = 0.864$), and overall comfort ($p = 0.002$, $r = 0.86$).

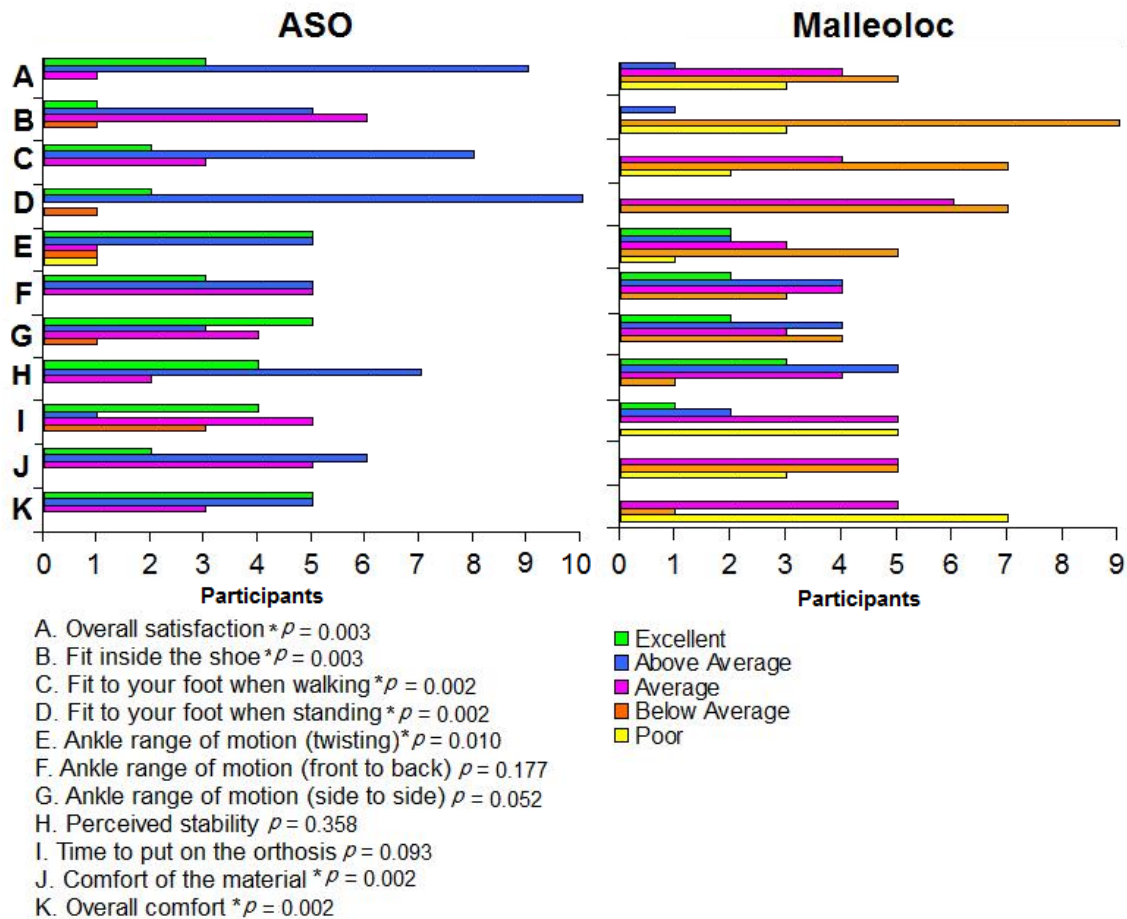


Figure 4.1. Participant's subjective comparisons of the ASO and Malleoloc orthoses for stability and comfort.

As shown in Figure 4.2, overall confidence with the orthosis ($p = 0.011$, $r = 0.703$), confidence in the cutting manoeuvre ($p = 0.018$, $r = 0.654$), confidence in sprinting ($p = 0.007$, $r = 0.753$), and confidence in front-to-back ankle movement ($p = 0.010$, $r = 0.711$) were significantly greater with the ASO compared to the Malleoloc. Participants also felt

significantly more confident with the ASO when exercising ($p = 0.001$, $r = 0.891$), walking ($p = 0.006$, $r = 0.764$), and standing ($p = 0.031$, $r = 0.598$).

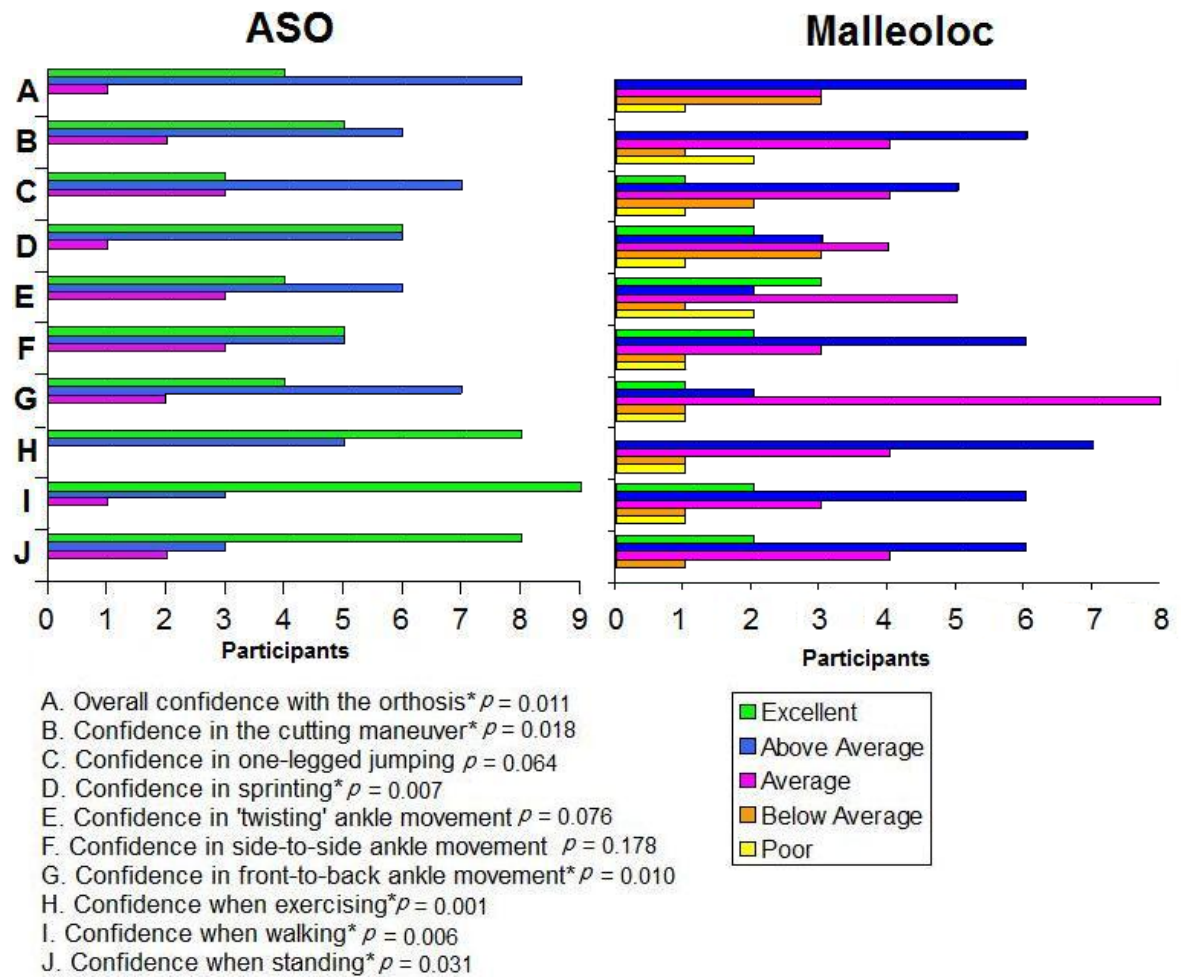


Figure 4.2. Participant's subjective comparisons of the ASO and Malleoloc orthoses for confidence.

When participants were asked what they liked best about the ASO, they reported stability (n=2), security (n=3), tighter fit (n=3), and fit into the shoe (n=2). Participants also liked that the laces were stitched to the tongue of the orthosis, and the padding of the tongue. They found the ASO to be small, easy to wash, quick and easy to apply, and

flexible/adjustable. Participants liked the overall comfort (n=2), confidence with the orthosis, and support. However, they also liked that there was a slight give to the ASO (not being too rigid). Participants appreciated having the ability to tighten the ASO once donned with the laces tied, and liked the 'horseshoe wrap' of the straps. They found the ASO material to be light, allow adequate movement, and the orthosis to be simple to don and doff (n=2). The ASO was perceived to feel like ankle taping. Participants liked the contouring of the straps around the heel, and one participant said the ASO gave 'peace of mind'.

There were contradictory remarks when participants were asked what they liked least about the ASO. They disliked the bulkiness (n=2), the fit inside shoes and cleats (n=2), the arch pain caused by the straps when worn too tightly, and the time to don and doff (n=3). Participants felt that the ASO was at times uncomfortable, disliked the rubbing of the orthosis that caused blistering over the Achilles tendon (n=2), and the irritation on the leg when the Velcro straps extend past the body of the orthosis. They did not like the thicker ankle cuff (n=2), having no way of decreasing the stability the ASO provides once ready to decrease dependency on the orthosis, and the restriction of too much front-to-back movement (plantar and dorsiflexion).

When participants were asked what they would improve about the ASO, they said make the orthosis less bulky, more comfortable, have a thinner tongue, shorten the Velcro straps, and find a way to go without laces. They suggested increasing the durability of the material, making the ASO adjustable so the wearer could reduce the level of dependency when ready, and make the material that goes over the Achilles tendon stiffer, but softer.

Participants (n=2) liked the starting point of the straps of ASO's new model, the EVO (evolution), which are inside the ankle sleeve. Two participants believed these inside straps offered better support, while another thought they were irritating.

Rating the Malleoloc, participants liked the colour, slimness, allowed range of motion, front-to-back movement, and the restriction of side-to-side movement (n=3). They also like the security (n=2), support, stability from the stiffness of the stirrup (n=2), adjustable Velcro, time to don and doff, and the ease of application. Participants found the Malleoloc to dry quickly and liked that the straps did not tangle.

Similar with the ASO, there were contradictory remarks when participants were asked what they did not like about the Malleoloc. They mentioned the reduced comfort (n=2), rigidity of the stirrup (n=2), mould to the foot, tightness around the leg and looseness around the ankle, and the lack of stability (n=2). Participants also did not like the fit inside shoes and cleats (n=5), that the stirrup caused pain and blisters on the bottom of the foot (n=3), and that the bottom of stirrup had to be worn under the orthotic/arch supports to increase comfort (n=4). They did not like how the Malleoloc was time-consuming to don (n=3), the quantity of loops for the straps, constantly adjusting straps because of poor hold of the Velcro (n=3), and that the crossover of the straps were irritating to the dorsum of the ankle, even when wearing socks (n=2). The participants disliked the Malleoloc's poor overall comfort (n=2), amount of padding worn to make the orthosis tolerable, irritation on Achilles tendon, irritation on the medial malleolus (n=2), prevention of front-to-back movement, and aggravation to the knees when wearing the orthosis (n=2).

Participants suggested improvements to the Malleoloc by increasing the padding on the inside of the stirrup (n=4) and adding padding that grips to the ankle. Most of the suggestions were regarding the Malleoloc's SRS, such as decreasing its rigidity (n=5), making the bottom less wide (n=3) and from softer and less-slippery material, and reducing the bulk (n=3), especially for narrow ankles and feet. Participants also suggested increasing the ergonomic fit of the stirrup, improving its ability to mould to the ankle, and flaring the top of stirrup edges for a better fit around the bottom of the calf. Recommendations for the straps were to soften the edges to reduce aggravation on the skin, create an easier strap system, raise the strap loop on the SRS and decrease its bulk. Two participants gave contradictory recommendations when one said to increase restriction of plantar and dorsiflexion, and the other said to add a hinge to the stirrup to increase plantar and dorsiflexion. Participants recommended increasing comfort to wear the Malleoloc over orthotics/arch supports, creating a second method of securing the orthosis in addition to the straps, and increasing overall comfort.

Participants made additional recommendations for the Malleoloc, such as the orthosis would be ideal for sports with less cutting and more jumping (i.e. Volleyball), attaching the strap loop to the stirrup to avoid loss, and improving the fit and comfort of straps to reduce chaffing. One participant said she would not buy the Malleoloc 'as is', but she liked the idea of its slim fit. Another complained that the stirrup made a hole in her insole and stretched the sides of her running shoes. Participants mentioned that once the Malleoloc was fastened to the ankle, there was great difficulty sliding the foot into the shoe because of reduced ankle ROM (n=2). Even if the easier method of donning the Malleoloc was to start by inserting the

orthosis in the shoe, followed by inserting one's foot into the orthosis, there were difficulties in passing the Velcro through the strap loop because this loop was further down inside the shoe. In addition, after only three weeks of use, the padding inside the stirrup of the Malleoloc started to unglue.

Chapter 5: Discussion

The ASO and the Malleoloc were designed to prevent ankle inversion injuries. Past research on ankle orthoses have proven that both soft lace-up and SRS orthoses successfully reduce the incidence of ankle injuries (Surve et al., 1994; Sharpe et al., 1997; Cordova et al., 2000, Dizon & Reyes, 2010). While injury factors have been investigated, the effects of these two orthosis designs on cutting, one-legged jumping and sprinting with footwear remained uncertain.

The ASO has a lace-up ankle sleeve and figure-8 straps to prevent abnormal ankle motion. The Malleoloc has a different system, which is a SRS with smaller straps. Sport participants often base their orthosis preferences on perceived support and comfort, but objective data is needed to support these perceptions. Therefore, hypotheses on objective data were formulated for this study: 1) ankle inversion and eversion ROM will be greater when using a soft orthosis, and 2) plantar-flexion and dorsiflexion ROM will be greater when using a SRS orthosis. The following sections examine these hypotheses.

5.1 Cut

In the cutting activity, the ASO allowed significantly more plantar-flexion than the Malleoloc during weight acceptance, when the planting foot came into contact with the ground to push off into another direction ($p = 0.038$, $d = 0.553$). The rigidity of the Malleoloc's stirrup was possibly the reason the orthosis restricted more plantar-flexion since the stirrup piece that goes under the heel may have prevented bending at the ankle. As the

ASO is less stiff, the participant's body weight upon weight acceptance could have overpowered the orthosis. Plantar and dorsiflexion angles were similar during midstance and pull-off. In addition, the plantar-flexion-dorsiflexion and dorsiflexion-plantar-flexion angle ranges were similar, meaning that the orthoses had similar effects on the ankle once the foot was on the ground.

The ASO also allowed greater angular velocity when plantarflexing, and the Malleoloc allowed greater angular velocity when dorsiflexing. The Malleoloc allowed faster dorsiflexion in comparison to plantar-flexion, possibly because the Malleoloc has one crossover strap on the anterior aspect of the ankle, situated higher than the strap on the ASO. These findings refute hypothesis 2), because the ASO generally allowed more plantar and dorsiflexion than the Malleoloc, and the results were not significant.

When looking at inversion and eversion, the peak eversion angle during weight acceptance of the planting foot was almost significantly greater with the Malleoloc ($p = 0.059$, $d = 0.5$). One structural distinction that could have contributed to this difference is the heel-orthosis interface. The Malleoloc stirrup had a wider base than the ASO sleeve. In addition, the soft ASO was tight to the participant's heel, while the semi-rigid Malleoloc base retained its shape. For many participants, the stirrup had gapping between the foot and orthosis on the lateral aspect of its base. This gapping could allow greater foot eversion. However, the ASO typically allowed more ROM in the frontal plane, perhaps because the medial aspect of the Malleoloc stirrup base was flush against the foot, the ankle, and the

shank, thereby preventing inversion. In the end, inversion and eversion ROM restriction was very similar for the soft and the SRS orthosis designs.

ASO inversion angular velocity was greater than the Malleoloc by nearly 100 degrees/second, although this difference was not significant. As stated in the paragraph above, the medial aspect of Malleoloc's SRS lies against the ankle, reducing movement. The ASO's soft material may not have restricted ankle motion as well as the Malleoloc's rigid stirrup during rapid movement. Both orthosis models had very similar eversion angular velocities in preparation for toe-off. These findings refuted hypothesis 1, because ASO plantar and dorsiflexion was not significantly greater compared to the Malleoloc.

5.2 One-Legged Jump

In jumping, no plantar-flexion and dorsiflexion angle differences were found between orthoses, refuting hypothesis 2). Both orthoses allowed very similar ROM (a difference of less than 1 degree) during each gait event. There were also similarities with dorsiflexion and plantar-flexion angular velocities, notably during the dorsiflexion during midstance where there was only a recorded difference of 0.21 deg/s between orthoses.

When looking at ankle inversion and eversion ROM, the Malleoloc allowed significantly greater movement during stance phase ($p = 0.048$, $d = 0.694$). This result was presumably caused by the gapping between the foot and the base of the stirrup. Inversion and eversion angles during all other events were similar between both orthoses. Angular velocities throughout the inversion and eversion ranges, and at different phases of jumping, were greater with the Malleoloc. Angular velocity was significantly greater for eversion-

inversion from midstance to toe-off in the one-legged jump ($p = 0.026$). This result could be caused by a decrease in ankle support during midstance with the Malleoloc because of the gapping at the base of the stirrup. Through a powerful movement, such as the one-legged jump push-off, the foot was able to invert and evert in the gap at the base of the stirrup. Angular velocities for other gait events were not significantly different between orthoses. Hypothesis 1) is refuted because ASO inversion and eversion was not significantly greater compared to the Malleoloc.

Jump height was not significantly different between ASO and Malleoloc groups ($p = 0.74$). The insignificant jump height results between the two orthosis groups support the findings of Gross et al. (1997), Rosenbaum et al. (2005), and Wiley & Nigg (1996). The latter two researchers also tested the Malleoloc.

5.3 Sprint

In sprinting, the ASO allowed greater peak plantar and dorsiflexion angles, and ranges of angles, by a few degrees throughout the gait phases. Sprinting is a very quick and powerful activity, and the soft material of the ASO possibly allowed slightly more plantar and dorsiflexion. However, these results were not significant and they refute hypothesis 2, since the Malleoloc did not significantly allow more plantar and dorsiflexion compared to the ASO. Ranges of motion of both orthoses were very similar. There might not have been a difference between the two orthoses during sprinting because of such quick weight-bearing mean times (ASO = 0.17 (0.02); Malleoloc 0.18 (0.02)), and increased ankle stiffness during

springing foot contact (running on the forefoot). Angular velocities between orthoses were similar for all gait events.

Inversion and eversion angles were similar between orthoses, refuting hypothesis 1. Generally, the Malleoloc allowed more inversion and eversion angular velocity during sprinting in comparison to the ASO. Perhaps the fit of the Malleoloc stirrup to the ankles of the participants, and the gapping at the base of the stirrup, did not restrict quick and minute movements as well as the enveloping ankle sleeve of the ASO.

5.4 Qualitative Outcomes

Participants were asked to subjectively rate their orthosis following each test session. When comparing ASO and Malleoloc outcomes, the ASO had significantly greater overall satisfaction, comfort, and confidence scores. The ASO was also considered better at disallowing twisting movements and giving confidence in restricting front-to-back ankle movement. The ASO was significantly easier to fit inside the shoe, and fit to the foot when standing and walking. There were no significant differences for perceived stability and time to put on the orthosis. Confidence when standing, walking, exercising, cutting and sprinting was also significantly greater with the ASO compared to the Malleoloc. However, no significant difference was found between orthoses for confidence when performing one-legged jumping, perhaps because the movement was so quick that the orthosis restrictions on ankle ROM were less noticeable than when performing the other movements.

5.4.1 The ASO

Participants had significantly greater confidence when wearing the ASO in comparison to the Malleoloc, perhaps due to perceived security from having a tight sleeve envelop the ankle, putting pressure on the skin's mechanoreceptors. This notion is supported by the research of Feuerbach et al. (1994) and Hertel et al. (1996) demonstrating that anesthetizing the ATLF ligament did not affect ankle proprioception, centre of balance and postural sway, indicating that cutaneous receptors could play a big role in providing proprioceptive information at the ankle. In addition, a study by Cordova et al. (2009) showed that cooling the ankle through cryotherapy did not affect the reflex response of the peroneus longus during ankle inversion perturbation.

One participant also mentioned that she liked how she could adjust/tighten the ASO while having her foot in her shoe. A few dislikes were the bulkiness of the ASO EVO cuff, blistering over the Achilles tendon and, the most reported, the time to don and doff the ASO. The preference of the figure-8 straps starting from the inside of the sleeve in the ASO EVO, instead of the outside, was inconclusive. One participant made an interesting point when she recommended having an orthosis that gave the wearer the option of decreasing levels of support throughout the recovery period to reduce orthosis dependency.

5.4.2 The Malleoloc

Participants liked the security the orthosis provided, the rigidity of the stirrup and, the most reported, side-to-side movement restriction. Qualitative results showed that there was no significant difference between orthoses for perceived stability. In addition, kinematic

results showed that the Malleoloc and ASO allowed similar side-to-side movement. The main complaints about the Malleoloc were the Velcro straps that did not hold well, the time to don, the pain and blistering at the bottom of the foot caused by the SRS, and the most reported complaint was the fit inside the shoe. This latter complaint was supported by a statistically significant greater satisfaction with ASO fit inside the shoe. The bulky stirrup was also responsible for the gapping at the base, and possibly the significant differences in ankle kinematics mentioned above.

A few participants indicated that the Malleoloc might be better suited to volleyball players who do not run as much as field-sport participants. Two participants claimed their knees would only hurt when wearing the Malleoloc. These symptoms might be supported the findings of Venesky et al. (2006) which state that wearing a SRS ankle orthosis when drop-landing significantly increased knee external rotation torque. In addition, Boros & Plumlee (2011) provide baseline kinematic data on the knee when wearing an ASO while performing 45 degree cuts, discovering that the ASO significantly reduced knee abduction (valgus) at initial ground contact.

The common suggestions to improve the Malleoloc were decreasing the rigidity of the SRS and increasing the amount of padding on the inside. In this study, the kinematic analysis showed that the Malleoloc did not restrict more side-to-side movement during activities, except during ground contact of the planting foot in cutting. This means the rigidity of the stirrup, in combination with Malleoloc's strapping system, did not significantly restrict more side-to-side movement. Therefore, increased stirrup rigidity might not be a factor in creating

stability. In addition, the participants did express a statistically significant preference in satisfaction with the ASO compared to the Malleoloc for overall comfort, and comfort of the material. Increased padding might help the Malleoloc prevent the pain and blistering caused by the base of the stirrup. In addition, the gapping at the base of the stirrup could decrease with more padding, or a softer stirrup material, but other measures would need to be taken to reduce the SRS's bulk and overall fit inside the shoe.

5.4.3 Comparison of results with other research

The ASO remains the most popular orthosis for the sport of Ultimate. The ASO is easily available in local stores and is half the price of the Malleoloc. In this study, there were no main significant differences in ankle motions when wearing either orthosis, throughout all activities. Our findings contradict those of Parsley et al. (2013) stating that the SRS in their study (Aircast Airstrip) significantly restricted more inversion than the ASO and the ASO significantly restricted more plantar-flexion, dorsiflexion, and eversion. DiStefano et al. (2008) found that the ASO restricted plantar-flexion at initial ground contact for jump-landing, which is similar to our findings where the ASO significantly reduced plantar-flexion at ground contact, but during planting of the foot in the cut activity. This latter result is similar to Gudibanda & Wang (2005) who also found the ASO to significantly reduce plantar-flexion at ground contact during a 45 degree cut activity. However, their testing was performed without running shoes. Additional findings showed that the ASO significantly decreased peak inversion in early, mid, and late stance phases of the cut activity, which were not replicated in this study. In this thesis, the kinematic similarities between the two orthoses

support the findings of Gross et al. (1997) and Rosenbaum et al. (2005) on performance outcomes.

The subjective results in this study are in accordance with those of Rosenbaum et al. (2005), who tested the Malleoloc. Participants perceived the Malleoloc to be easier to handle and the lace-up more comfortable. However, participants in this study did not find that the Malleoloc SRS provided more support. Participants preferred the soft lace-up orthosis to the Malleoloc SRS, which contradicts the findings of Alves et al., (1992) and Greene & Wight (1990) where participants preferred the SRSs to the soft lace-up orthosis. In the study of Simpson et al. (1999), the Malleoloc was the orthosis of choice for stability and overall performance compared to a soft orthosis and another SRS orthosis. Unlike in the study of Gudibanda & Wang (2005), participants in this thesis were not given a Likert scale for subjective ratings of the orthoses. However, in both studies, participants gave the ASO good ratings for comfort and support, but participants in this thesis did not believe the ASO was easy to apply. In Beriau et al. (1994) and Verbugge (1996), participants found that the SRS (Aircast) provided excellent support and comfort, which contradicts the findings in this thesis where participants did not share these views on the SRS (Malleoloc). Participants in this thesis shared the opinions of participants in the study by Gross et al. (1997), stating that the SRS was bulky and gave some of them blisters on their foot. In summary, evidence shows that preference for soft or SRS orthoses varies.

Chapter 6: Conclusion

This study was performed to fill the gap in research on ASO and Malleoloc kinematics and performance. Although there were a few significant differences on ankle kinematics between the two orthoses, the orthoses generally allowed similar ankle movement. Most participant perceptions on the two orthosis models were statistically significant, with the ASO having higher ratings. There was no significant difference on perceived stability between the two orthoses; however, participants had significantly more confidence when wearing the ASO over the Malleoloc. This increased confidence could be due to the greater comfort level with the ASO, and having the soft lace-up sleeve envelop the ankle, possibly increasing the participant's proprioception levels through cutaneous mechanoreceptors.

Hypothesis 1), ankle inversion and eversion ROM will be greater when using a soft orthosis, was refuted because most results were not significant. Hypothesis 2), plantar-flexion and dorsiflexion ROM will be greater when using a SRS orthosis, was refuted because significant results were only found for one gait event of one activity (the cut). However, the ASO typically allowed more plantar and dorsiflexion, although not significantly. Greater ankle motion with the ASO may have been due to its softer material and the loosening of the laces throughout activity. Soft and SRS orthoses have different designs and are made of different materials, but they support the ankles in similar ways. Therefore, field-sport participants may choose either orthosis design as they have similar kinematic effects on the ankle. However, participants may prefer one design over the other based on perceived levels of comfort and stability.

6.1 Future Research

Based on the study outcomes, future research should be considered for identifying the role of skin contact on proprioception. Previous research showed that cutaneous receptors could play a more important role in ankle proprioception than the ATFL. Therefore, comparing the ASO lace-up sleeve to an identical one without straps would enable the discovery of the importance of the figure-8 straps. If the straps of the ASO do not provide a significant improvement in ankle stability, they should be removed to offer an increased ease of application and to decrease the bulkiness and irritation to the foot and ankle. Furthermore, compressive elastic sleeves that do not have laces could also be compared to the ASO and ASO with the straps removed. If proven effective, these elastic sleeves would offer an even greater ease of application and comfort.

There were good intentions when designing a slimmer ankle orthosis model such as the Malleoloc, but this SRS did not provide more support and caused irritation to the ankle and foot. A softer material for the stirrup, or stirrup base, might not offer any less support and could make a slimmer, more comfortable, orthosis. The rigidity of the stirrup could have been the factor that caused knee pain when wearing the Malleoloc for two participants in this study. Kinematics of the knee when wearing ankle orthoses, especially SRSs, during physical activity should be investigated to gain a better understanding of the effects of orthoses on the lower-body kinetic chain, and build on new discoveries in this area.

The design of an orthosis with optional strapping could benefit participants who want to decrease their dependency levels on the orthosis as they regain strength in their ankle. The

ASO could provide a loop for the figure-8 straps if needed. The ASO's older, basic model already has 'stays', rigid plastic pieces, that can be removed from medial and lateral compartments on the lace-up sleeve. The Malleoloc could adopt a similar system where rigid plastic pieces could be inserted or removed from the stirrup for wearers who prefer a softer stirrup, or who would like to decrease dependency on the orthosis.

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Appendix A: Recruitment Letter



**The Ottawa
Hospital** | **L'Hôpital
d'Ottawa**

Comparison of Ankle Kinematics between Soft and Semi-Rigid Ankle Orthoses for Field-Sport Activities

In the world of field sports, ankle sprains are one the most common injuries. Therefore, many people wear ankle orthoses, sometimes called ankle braces, to prevent ankle injuries, increase ankle stability, or help with rehabilitation after an ankle injury. However, ankle orthosis designs vary from one brand to the next, and each brand has a different effect on ankle range of motion.

This research project will provide a better understanding of the effects of the ASO and Malleoloc orthosis designs on ankle movement in field sports. The Malleoloc is a semi-rigid orthosis, with a rigid stirrup-shaped piece and two straps. This design will be compared with the ASO lace-up orthosis, a soft brace with an ankle sleeve, laces, and 'figure-8' straps.

Ultimate players who have worn an ankle orthosis on a regular basis during activity, for at least three weeks, are eligible to participate in the experimental group of the study. All eligible participants must have a minimum of one year of competitive Ultimate experience to participate in the study. Two testing sessions will be conducted a minimum of three weeks apart: one with the ASO lace-up orthosis and the other with the Malleoloc orthosis. Participants will be asked to perform three Ultimate-related, field-sport movements: sprinting, one-legged jumping, and cutting. Lower-body limb movements will be recorded to identify differences at the hip, knee, ankle and foot.

- All motion analysis testing will take place at The Ottawa Hospital Rehabilitation Centre, Rehabilitation Technology Lab, on tile flooring.
- You are asked to wear tight-fitted clothing, without reflective material, to reduce marker movement during activity. You should wear your typical indoor running shoes during testing, providing they are not ripped nor broken.

- A researcher will review the study protocol with you, and you will be asked to sign a consent form. If you are part of the orthosis group, you will be asked to fill out *Part A* of a questionnaire that contains questions about past ankle injuries, perceived orthosis comfort, etc.
- Body measurements and ankle range of motion will be recorded at the beginning of your testing session.
- We will provide you with a new orthosis that you should wear during all your physical activity sessions when needed. After three weeks, you will complete testing session one. After testing session one, you will be given a different orthosis which you will wear during all your physical activity sessions when needed for a minimum of three weeks. You will then be asked to return for testing session two.
- Each testing session will last approximately three hours.
- During your testing session, reflective markers will be taped to your torso and lower-body so that motion analysis cameras can track your movements.
- The testing will involve three tasks:
 - 10 m sprint, five repetitions
 - sprinting to one-legged jump, three repetitions
 - sprinting to making a 45° cut, three repetitions
- After the testing, if you filled out *Part A* of the questionnaire, you will be asked to fill out *Part B* to answer questions about ankle range of motion and comfort during testing.
- You may rest or take a break, at any time during the testing.
- You may also refuse to perform any movements at any time.
- You will receive \$25.00 for parking and travelling expenses per session.
- Accessible changing rooms and washrooms are available on site.

If you would like to participate in the study or if you have any questions, please contact XXXXXXXXXXXXXXXXXXXXXXXX.

Appendix B: Consent Form

Information Sheet and Consent Form



The Ottawa
Hospital | L'Hôpital
d'Ottawa

Comparison of Ankle Kinematics between Soft and Semi-Rigid Ankle Orthoses for Field-Sport Activities

Principal Investigator: XXXXXXXXXXXXXXXXXXXXXXXXXXXX

Sponsor: XXXXXXXXXXXXXXXXXXXXXXXXXXXX

Introduction

You are being asked to participate in this research project since you wear an ankle orthosis on a regular basis when you play Ultimate. You will be asked to participate in the testing with an ankle orthosis at all times.

Please read this Patient Information Sheet and Consent Form carefully and ask as many questions as you like before deciding whether to participate in this research study. You can discuss this decision with your family, friends and your health care team.

Background, Purpose and Design of the Study

In field sports, ankle sprains are one of the most common injuries. Therefore, many people wear ankle orthoses (braces), to prevent ankle injuries, increase stability, or help with rehabilitation after an injury. However, orthosis designs vary and each model has a different effect on ankle range of motion.

This research project will provide a better understanding of the effects of the ASO (Ankle Stability Orthosis) and Malleoloc orthosis designs on ankle movement and stability in field sports. The Malleoloc is a semi-rigid orthosis, with a rigid stirrup-shaped piece and two straps. This design will be compared with the ASO lace-up orthosis, a soft brace with an ankle sleeve, laces, and a 'figure-8' strap.

Ultimate players who wear an ankle orthosis on a regular basis during activity and who have not sustained an injury to a part of their lower-body, preventing them from participating in their regular physical activity for a minimum of a week, within the last six months, are eligible to

participate in this study. You must have a minimum of one year of competitive Ultimate experience. Participants must participate in a minimum of two exercise sessions per week, such as an Ultimate session, a sprint-training session, a weight training session, or exercise with quick changes in direction/fast push-offs. You will start by wearing one of the Malleoloc or the ASO orthoses for three weeks during physical activity, just as you would typically wear your current ankle orthosis, and then participate in a testing session wearing that same orthosis. When you are given an orthosis for testing, we ask that you to leave all your other orthoses with the research team to encourage you to only wear the orthosis with which you are being tested prior to your testing session. You will sign the consent form upon receiving your first orthosis. You will then repeat these directions with the other ankle orthosis. At each testing session, you will be asked to perform three one-legged jumps, three cuts and five sprints to ensure that we capture proper foot ground contact in the capturing volume. Lower-body limb movements will be recorded to identify differences at ankle.

Study Procedures and or Description of Treatment

Upon arrival at the Ottawa Hospital Rehabilitation Centre Rehabilitation Technology Laboratory for the three-hour testing session, you will be asked to change into your body-fitted testing clothes. Afterwards, the research team will record the length of your limbs, your height, and your weight. The research team will then evaluate your ankle range of motion.

During testing, you will have a series of reflective markers taped to anatomically landmarks of your lower-body to track body motion. You will perform five trials of sprinting, three trials of one-legged jumping, and three trials of 45-degree cutting (total of 11 trials) in your running shoes. The order of testing for these three movements will be randomized. The cutting manoeuvre consists of a five meter run to a marked location on the floor, a plant with the leg that has the orthosis, and a sprint at 45° from the first sprint path. If you typically wear an orthosis on each foot, you will double the amount of trials for the jumping and cutting manoeuvres in order to record planting for both feet. You may rest as needed between trials. You will be asked to follow a member of the research team for a 10 minute warm-up, and unlimited extra warm-up time will be available as needed.

Should you agree to participate in this study, a member of the research team will take your ankle measurements before ordering your orthoses.

Study Duration

The study will take place over a four-month period. You are asked to participate in two separate testing sessions, each lasting approximately three hours.

Possible Side Effects and/or Risks

The risks in the study are very rare and include being fatigued from the movement trials, as well as sustaining a physical injury while running, jumping, or cutting. Risks are minimized by providing a flat, clean, and predictable running surface and testing environment.

Benefits of the Study

You will have the option of keeping the new Malleoloc and ASO orthoses that you will have received for your testing sessions. Your participation in this research may allow the researchers to discover the biomechanical differences of wearing a soft and a semi-rigid orthosis during field-sport movements. This may help people choose the appropriate type of ankle orthosis for their physical activities.

Withdrawal from the Study

You have the right to withdraw from the study at any time without any impact to your current and future care at the Ottawa Hospital. If you decide to withdraw, you should discuss this with the primary investigator and provide an explanation to the research team. You will not have the option of keeping the ankle orthoses for personal use.

You have the right to check your study records and request changes if your information is incorrect. However, to ensure the scientific integrity of the study, some of your records related to the study may not be available for your review until after the study has been completed.

Compensation

In the event of a research-related injury or illness, you will be provided with appropriate medical treatment/care. You are not waiving your legal rights by agreeing to participate in this study. The study doctor and the hospital still have their legal and professional responsibilities.

Study Costs

You will be given \$25 for each of your testing sessions at the laboratory to help cover transportation and parking costs.

Confidentiality

All personal health information will be kept confidential, unless release is required by law. Representatives of the Ottawa Hospital Research Institute may review your study records under the supervision of XXXXXXXXXXXXXXXXXXXXXXXXXXXX for audit purposes.

You will not be identifiable in any publications or presentations resulting from this study. No identifying information will leave the Ottawa Hospital. All information that leaves the hospital will be coded with an independent study number.

The link between your name and the independent study number will only be accessible by XXXXXXXXXXXXXXXXXXXXXXXXXXXX. The link and study files will be stored separately and securely. Both files will be kept for a period of 15 years after the study has been completed. All paper records will be stored in a locked filing cabinet and office. All electronic records will be stored on The Ottawa Hospital network and protected by a user password, again only accessible by XXXXXXXXXXXXXXXXXXXXXXXXXXXX. At the end of the retention period, all paper records will be disposed of in confidential waste, or shredded, and all electronic records will be deleted.

Voluntary Participation

Your participation in this study is voluntary. If you choose not to participate, your decision will not affect the care you receive at this Institution at this time, or in the future. You will not have any penalty or loss of benefits to which you are otherwise entitled.

New Information about the Study

You will be told of any new findings during the study that may affect your willingness to continue to participate in this study. You may be asked to sign a new consent form.

Questions about the Study

If you have any questions about this study or if you feel that you have experienced a research-related injury, please contact XXXXXXXXXXXXXXXXXXXXXXXXXXXX.

The Ottawa Hospital Research Ethics Board (OHREB) has reviewed this protocol. The OHREB considers the ethical aspects of all research studies involving human subjects at The Ottawa Hospital. If you have any questions about your rights as a research subject, you may contact the Chairperson of the Ottawa Hospital Research Ethics Board at XXXXXXXXXXXXXXXXXXXXXXXX.

Consent Form

Comparison of Ankle Kinematics between Soft and Semi-Rigid Ankle Orthoses for Field-Sport Activities

Consent to Participate in Research

I understand that I am being asked to participate in a research study about the biomechanical effects of wearing a soft versus a semi-rigid ankle orthosis when performing field-sport type movement. This study has been explained to me by XXXXXXXXXXXXXXXX.

I have read this five-page Patient Information Sheet and Consent Form, or have had this document read to me. All my questions have been answered to my satisfaction. If I decide that I would like to withdraw my consent at a later stage in the study, I may do so at any time.

I voluntarily agree to participate in this study.

A copy of the signed Information Sheet and/or Consent Form will be provided to me.

Signatures

Participant's Name (Please Print)

Participant's Signature

Date

Investigator Statement (or Person Explaining the Consent)

I have carefully explained to the research participant the nature of the above research study. To the best of my knowledge, the research participant signing this consent form understands the nature, demands, risks and benefits involved in participating in this study. I acknowledge my responsibility for the care and wellbeing of the above research participant, to respect the rights and wishes of the research participant, and to conduct the study according to applicable Good Clinical Practice guidelines and regulations.

Name of Investigator/Delegate (Please Print)

Signature of Investigator/Delegate

Date

Appendix C: Ankle Orthosis Questionnaire

Comparison of Ankle Kinematics between Soft and Semi-Rigid Ankle Orthoses for Field-Sport Activities	Date (dd/mm/yy)
--	-----------------

Name		Age		Gender	☐ M ☐ F
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PART A:

1. Current reason for wearing an ankle orthosis (mark all that apply)?

Past Injury (please specify)
Joint laxity
Security/injury prevention
I don't know why I'm still wearing an ankle orthosis
Other (please specify):

2. How long have you been wearing your orthosis?

3 weeks	1-6 months	6 months - 1 year	1- 2 years	Over 2 years
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3. On which foot do you wear your orthosis?

Right	Left	Both
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4. Which foot is your dominant foot:

5. Usually, you wear your orthosis at all times during:

Ultimate only	Ultimate and a few other activities	Most physical activities	All physical activities
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PART B

6. Testing orthosis model: ASO ☐ Malleoloc ☐

7. Please rate the following items for the ankle orthosis tested by placing a mark (×) in the appropriate box.

	Poor	Below Average	Average	Above Average	Excellent
Overall comfort					
Comfort of the material					
Time to put on the orthosis					
Perceived stability					
Ankle range of motion (side to side)					
Ankle range of motion (front to back)					
Ankle range of motion (twisting)					
Fit to your foot when standing					
Fit to your foot when walking					
Fit to your foot during the testing					
Fit inside your shoe					
Overall satisfaction					

8. Please rate your level of confidence and security when wearing the orthosis by placing a mark (×) in the appropriate box.

	Poor	Below Average	Average	Above Average	Excellent
Confidence when standing					
Confidence when walking					
Confidence when exercising					
Confidence in front-to-back ankle movement					
Confidence in side-to-side ankle movement					
Confidence in 'twisting' ankle movement					
Confidence during the testing in sprinting					

Confidence during the testing in one-legged jumping					
Confidence during the testing in the cutting manoeuvre					
Overall confidence with the orthosis					

9. What footwear did you predominantly wear in combination with the present orthosis, outside of testing (circle all that apply)?

Soccer cleats	Ultimate cleats	Football cleats	High-top running shoes	Low-top running shoes
Other Athletic shoes	Casual shoes	Sandals	Business/Dress shoes	No shoes

10. Comments

What do you like best about the orthosis?	
What do you like least about the orthosis?	
How would you improve the orthosis?	
Additional Comments	

Appendix D: Subject Data Sheet

Subject Name		#
Date (dd/mm/yy)		
Orthosis	ASO ☐ Malleoloc ☐	
Shoe size		
Orthotics/Arch support inserts	Yes, I wear them during activity ☐ No, I don't own a pair/ I rarely wear them ☐	
Mailing Address		

Foot deformities (check all that apply)

☐ Knock foot (valgus foot)	☐ Flat foot (pes planus)
☐ Splay foot	☐ Hollow foot (pes varus, pes cavus)
☐ Bunions	☐ Plantar fasciitis
☐ Heel Spurs	☐ Hammer Toes
☐ Calluses	☐ Achilles Tendonitis
☐ Arthritis	☐ Blisters

Pressure points / chafing / pain

Location	Description

Orthosis

Model	
Inversion with cleats (deg)	
Inversion without cleats (deg)	
Plantar-flexion with cleats (deg)	
Plantar-flexion without cleats (deg)	
Location of padding	
Comments	

Measurements

Body Mass (kg)	
Height (mm)	
Inter-ASIS distance (mm)	
Inter-PSIS distance (mm)	
Right leg length (mm)	
Left leg length (mm)	
Right Knee width (mm)	
Left Knee width (mm)	
Right Ankle width (mm)	
Left Ankle width (mm)	
Right ASIS-Trochanter distance (mm)	
Left ASIS-Trochanter distance (mm)	
Right Foot length (mm)	
Left Foot length (mm)	
Right Sole Thickness (mm)	
Left Sole Thickness (mm)	
Right Tibial Torsion (deg)	
Left Tibial Torsion (deg)	

Appendix E: Marker Set

6 Degrees of Freedom Marker Set

