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Effect of simulated joint instability and bracing on ankle and subtalar joint flexibility

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ABSTRACT

It is clinically challenging to distinguish between ankle and subtalar joints instability in vivo. Understanding the changes in load-displacement at the ankle and subtalar joints after ligament injuries may detect specific changes in joint characteristics that cannot be detected by investigating changes in range of motion alone. The effect of restricting joints end range of motion with ankle braces was already established, but little is known about the effect of an ankle brace on the flexibility of the injured ankle and subtalar joints. Therefore, the purposes of this study were to (1) understand how flexibility is affected at the ankle and subtalar joints after sectioning lateral and intrinsic ligaments during combined sagittal foot position and inversion and during internal rotation and (2) investigate the effect of a semi-rigid ankle brace on the ankle and subtalar joint flexibility. Kinematics and kinetics were collected from nine cadaver feet during inversion through the range of ankle flexion and during internal rotation. Motion was applied with and without a brace on an intact foot and after sequentially sectioning the calcaneofibular ligament (CFL) and the intrinsic ligaments. Segmental flexibility was defined as the slope of the angle-moment curve for each 1 Nm interval. Early flexibility significantly increased at the ankle and subtalar joint after CFL sectioning during inversion. The semi-rigid ankle brace significantly decreased early flexibility at the subtalar joint during inversion and internal rotation for all ligament conditions and at the ankle joint after all ligaments were cut.

1. Introduction

Instability to the ankle joint complex usually result from ankle sprains. The daily rate of ankle sprains is estimated to be of 1 in 10,000 people in the United States (Waterman et al., 2010) and 5600 per day in the UK (Doherty et al., 2014), they are one of the most common injuries in the military (Doherty et al., 2014), and the ankle is the most re-injured body part in high school athletics (22.3% of recurrent injuries), and the second most frequent new injury (15.8%) (Welton et al., 2018). When a patient presents with lateral instability in the ankle joint complex, approximately 25–75% of cases have subtalar joint instability, either in isolation or in combination with ankle instability (Hertel et al., 1999; Mittlmeier and Wichelhaus, 2015). However, subtalar joint instability is nearly impossible to differentiate from ankle instability (Aynardi et al., 2015) because the anatomy of the ankle joint complex makes it difficult to isolate the motion of the talus with respect to the tibia and the calcaneus. Therefore, subtalar joint instability combined with ankle joint instability may not be adequately diagnosed which may lead to long term complications such as chronic ankle instability (Anandacoomarasamy and Barnsley, 2005; Rubin, 1962).

Clinical examination after an acute ankle sprain can be followed by stress radiographies to determine the talar and subtalar tilts and evaluate the instability at the hindfoot (Ahovuo et al., 1988; Bahr et al., 1997; Becker et al., 1993; Beynnon et al., 2005; Blanshard et al., 1986; Budny, 2004; Christensen et al., 1986; Frost and Amendola, 1999; Harper, 1992; Ishii et al., 1996; Johannsen, 1978; Laurin et al., 1968; Raatikainen et al., 1992; Riegler, 1984; Rijke and Vierhout, 1990). However 2D radiographs do not provide sufficient information on the site and extent of ligament injuries. Kinematics analysis became commonly used in vitro to better understand the differences in range of motion (ROM) at the ankle and subtalar joints after sectioning the lateral ligaments (Bonnel et al., 2010; Cass et al., 1984; Cass and Settles, 1994; Choisne et al., 2013; Choisne et al., 2012; Lundberg et al., 1989a;

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Lundberg et al., 1989b; Lundberg et al., 1989c; Ringleb et al., 2011; Ringleb et al., 2005; Rosenbaum et al., 1998; Siegler et al., 1988). Conflicting results across studies were attributed to the disparity in measurement methods used, the forces applied to the foot and the definition in the joints studied (talus-tibia and calcaneus-tibia). In order to properly identify subtalar joint instability in clinical situation, additional methods of analysis should be investigated. Such method would be to combine the kinematics and applied load to characterize the load-displacement and flexibility at the ankle and subtalar joints (Chen et al., 1988). Because the ankle joint complex exhibits non-linear load-displacement characteristics, the ankle flexibility tends to be higher in early stage and plateau when approaching the end ROM. Some studies showed that damage to the ankle lateral ligaments causes specific and detectable changes in flexibility, especially in the early stage of anterior drawer and inversion (Lapointe et al., 1997). However, none of these studies looked at the flexibility of the subtalar joint and if differentiable changes occurred at the ankle and subtalar joint depending on the injured ligament during combined inversion and flexion of the foot and during internal rotation.

Non-operative treatment combined with further injury prevention is essential given the indistinct nature of ligament injury at the ankle joint complex. The use of a semi-rigid brace was previously shown to limit the inversion end range of motion (Lee et al., 2012; Nishikawa et al., 2000; Tohyama et al., 2006) of the subtalar (Kamiya et al., 2009) and ankle joint (Choisne et al., 2013; Eils et al., 2007; Lee et al., 2012; Shapiro et al., 1994; Siegler et al., 1997; Tang et al., 2010; Tohyama et al., 2006; Ubell et al., 2003; Zhang et al., 2009). However these studies provided a limited view of the function of bracing as the restriction in ROM only is not sufficient to describe the protective characteristics of the brace. One study investigated the effect of four ankle braces on the hindfoot flexibility in vivo on healthy volunteers (Siegler et al., 1997). More information is needed to understand the effect of an ankle brace on the flexibility of the injured ankle and subtalar joints and provide insight into the effectiveness of the bracing applications.

The purposes of this study were to (1) understand how flexibility is affected at the ankle and subtalar joint after the CFL is sectioned in isolation and in combination with the cervical and interosseous talocalcaneal ligaments during inversion, combined sagittal foot position and inversion and during internal rotation and (2) investigate the effect of a semi-rigid ankle brace on the ankle and subtalar joints flexibility after instability was created at the hindfoot.

2. Methods

The details of the data collection were previously published elsewhere (Choisne et al., 2013). Nine fresh-frozen cadaveric lower extremities (7 left, 2 right, age 66 ± 9 years, 3 female and 6 male) were sectioned approximately 20 cm above the lateral malleolus. The ankle joint complex (i.e., the bones and soft tissues surrounding the tibia, fibula, talus, and calcaneus, often referred to as the hindfoot) was examined manually by an Athletic Trainer to confirm that no instability or other pathology was present.

An incision placed on the lateral side of the ankle exposed the ligaments. The Achilles tendon was sectioned and sutured to a 44.5 N weight (Tohyama et al., 2006). Each specimen was placed into a custom six degree-of-freedom positioning and loading device (Ringleb et al., 2011). The tibia and fibula were fixed using a clamp and stainless steel k-wires and a 44.5 N axial load was applied to the tibia. The calcaneus was fixed to the foot plate using bone screws inserted into the calcaneus. The foot plate was moved with one hand using a handle to apply forces. An athletic trainer moved the ankle joint complex as if a clinical evaluation was being performed (Fig. 1).

Kinematic data were collected with a 6 camera Motion Analysis Eagle System (Motion Analysis Corporation, Santa Rosa, CA) in combination with the MotionMonitor (Innovative Sports Training, Chicago, IL) at a sampling rate of 150 Hz. Custom-made *retro*-reflective sensors were screwed on the calcaneus, talus and tibia. The talus sensor was placed on the anterior medial part making sure the extensor retinaculum was kept intact. A force/torque transducer (ATI mini45, ATI Industrial Automation, Apex, NC) was placed between the foot plate and the handle to record the applied moment during the movement of the foot. Line levels were attached to the foot plate and were used as guides to assure that the foot returned to a neutral position after each trial. Line levels also ensured that inversion at the foot was applied as a single rotation around the anterior-posterior axis of the foot so that no internal/external coupled rotation occurred.

Inversion was applied to the ankle joint complex with the foot placed in neutral sagittal position (90°), in maximum dorsiflexion and in maximum plantarflexion. The ankle joint complex was also moved to maximum internal rotation with the foot placed in neutral sagittal position. Motions were applied with and without a semi-rigid ankle brace (Fig. 1) with a hinge joint at the ankle (Active Ankle T2, Cramer Products, Gardner, KS) on an intact ankle joint complex, after the CFL was sectioned and after further injury to the intrinsic ligaments (i.e. the cervical ligament and the interosseous talocalcaneal ligament). For each motion and condition, the foot was manipulated to the end range of motion until no further motion at the joint complex could be observed.

Motion of the ankle was defined as the talus relative to the tibia, subtalar joint motion was defined as the calcaneus relative to the talus and the ankle joint complex motion was defined as the calcaneus relative to the tibia. The body reference frame for the tibia, talus and calcaneus were defined according to the recommendations from the International Society of Biomechanics (ISB) (Wu et al., 2002). The x-axis was oriented from posterior to anterior, y-axis pointed up, and the z-axis pointed from medial to lateral. Rotations were calculated from neutral to maximum motion. Sensor data were exported from The Motion Monitor using an X-Z'-Y'' Euler rotation sequence for the subtalar joint and a Z-X'-Y'' Euler sequence for the ankle joint (Choisne et al., 2012). The Euler angles versus the moment applied to the foot was plotted from one loading/unloading cycle for each joint, each condition, each motion and each specimen. The loading portion of the angle - moment curve was divided into four equal intervals from zero to the minimum common maximum moment for all conditions and specimen. This minimum common maximum moment was 4 Nm for inversion in neutral sagittal position, inversion in maximum dorsiflexion and

Fig. 1. Experimental setup with the foot in the ankle brace and the three markers attached to the calcaneus, talus and tibia.

inversion in maximum plantarflexion and set to 3.8 Nm for internal rotation.

Segmental flexibility was defined as the slope of the angle - moment curve for each interval (S1 representing the beginning of the curve and S4 the end) (Fig. 2). Differences in segmental flexibility between conditions (intact, sectioned CFL, and serially sectioned CFL, cervical and ITCL ligaments, barefoot and braced) were initially examined using the Friedman test for each interval. In the presence of a condition main effect, post hoc comparisons were made using Wilcoxon signed-rank tests. Statistical significance was set at $p < 0.05$ for all analyses. All statistical tests were conducted using SPSS (Version 21, SPSS Inc, Chicago, IL).

3. Results

Flexibility characteristics on sectioned ligaments

Sectioning the CFL significantly increased the subtalar ($p = 0.008$), ankle ($p = 0.011$) and ankle joint complex ($p = 0.008$) early flexibility (segment 1) compared to intact when inversion was applied with the foot held in neutral sagittal position (Fig. 3). CFL disruption also increased segment 2 ($p = 0.038$) and 3 ($p = 0.015$) flexibility at the ankle during inversion (Fig. 3b). When inversion was applied with the foot held in maximum dorsiflexion (Fig. 4), early flexibility (segment 1) and late flexibility (segment 4) at the ankle ($p = 0.028$ and $p = 0.008$, respectively) and ankle joint complex ($p = 0.038$ and $p = 0.011$, respectively) increased with sectioning of the CFL. Holding the foot in plantarflexion (Fig. 5) increased subtalar ($p = 0.028$) and ankle joint complex ($p = 0.011$) early flexibility (segment 1).

Additional sectioning of the cervical and interosseous talocalcaneal ligament led to increase in early flexibility for the subtalar ($p = 0.011$) and ankle joint complex ($p = 0.008$) joints and in all segmental flexibility at the ankle joint ($p = 0.008$ for seg.1, $p = 0.028$ for seg. 2, $p = 0.008$ for seg. 3 and $p = 0.021$ for seg. 4) during inversion (Fig. 3). Total sectioning of all ligaments increased late flexibility at the ankle joint complex ($p = 0.038$ for seg. 3 and $p = 0.038$ for seg. 4) during inversion with the foot dorsiflexed (Fig. 4) and increased in segment 2 flexibility at the ankle ($p = 0.038$) during inversion with the foot in plantarflexion (Fig. 5).

Internal rotation did not influence flexibility at the subtalar, ankle and ankle joint complex joints after cutting the CFL alone and in combination with the intrinsic ligaments (Fig. 6).

4. Flexibility characteristic on semi-rigid ankle brace

Appling a semi-rigid ankle brace to the foot significantly decreased segmental 1 and 2 flexibility at the subtalar joint during inversion for all sagittal foot position (Figs. 3–5) and in segment 1 flexibility during internal rotation for all ligament conditions (Fig. 6).

At the ankle, the brace limited early flexibility after sectioning the CFL alone ($p = 0.021$, Fig. 3b) and in combination with the intrinsic ligaments ($p = 0.008$, Fig. 3b) and continued restricting segment 2 flexibility after all ligaments were cut during inversion ($p = 0.008$, Fig. 3b). The brace also restricted flexibility at the ankle when the foot was in dorsiflexion and inversion was applied (Fig. 4b) in the intact foot (segment 2, $p = 0.011$) after sectioning of the CFL (segment 1, $p = 0.038$)) and after disruption of all ligaments (segment 3, $p = 0.028$)). During plantarflexed inversion the brace limited flexibility at the ankle (Fig. 5b) in the intact foot (segment 1 and 2, $p = 0.038$ and 0.015), after sectioning the CFL (segment 2, $p = 0.015$) and after all ligaments were cut (segment 1, $p = 0.015$). During internal rotation the brace limited early flexibility after all ligaments were cut at the ankle (Fig. 6b, $p = 0.038$). Additionally, segment 2 flexibility was significantly higher when no ligaments were cut ($p = 0.008$), the CFL was cut ($p = 0.008$) and the intrinsic ligaments were cut ($p = 0.021$) when the brace was worn during internal rotation at the ankle (Fig. 6b).

5. Discussion

The first purpose of this study was to determine how flexibility was affected at the subtalar joint, ankle and ankle joint complex after sequential sectioning of the CFL, cervical ligament and interosseous talocalcaneal ligament during inversion combined with different sagittal foot position and internal rotation. The present study found that early flexibility (segment 1) significantly increased at the subtalar joint after CFL sectioning when inversion was applied in neutral sagittal position and in maximum plantarflexion. Additional sectioning of the intrinsic ligaments significantly increased early flexibility at the subtalar joint in inversion with the foot in neutral sagittal position. Flexibility analysis showed that sectioning the CFL alone increased subtalar early flexibility while some studies reported the inversion end range of motion did not statistically increased at the subtalar joint when

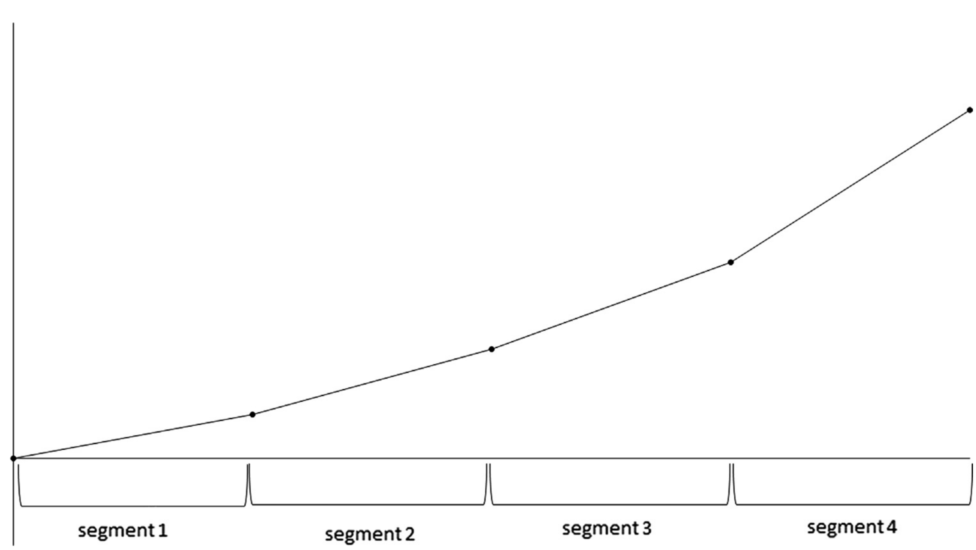


Fig. 2. Example of the derivation of segmental flexibility from the moment-angular displacement curve. In red the 4 segmental flexibility (s1 to s4).

Segment 1

	Int		
Int+b	0.008		
CFL	0.008	CFL	
CFL+b	-	0.008	
All cut	0.011	NS	All
All+b	-	-	0.008

Segment 2

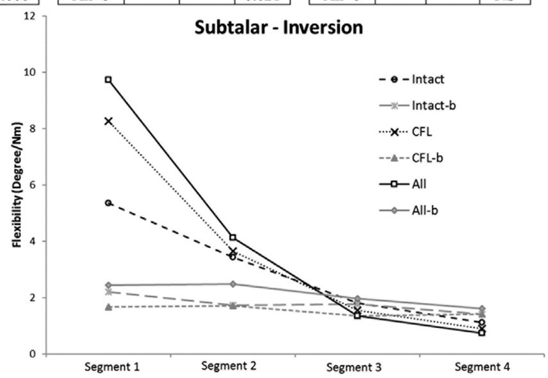
	Int		
Int+b	0.028		
CFL	NS	CFL	
CFL+b	-	0.021	
All cut	NS	NS	All
All+b	-	-	0.021

Segment 3

	Int		
Int+b	NS		
CFL	NS	CFL	
CFL+b	-	NS	
All cut	NS	NS	All
All+b	-	-	NS

Segment 4

Friedman's test
p = 0.071



A

Segment 1

	Int		
Int+b	NS		
CFL	0.011	CFL	
CFL+b	-	0.021	
All cut	0.008	NS	All
All+b	-	-	0.008

Segment 2

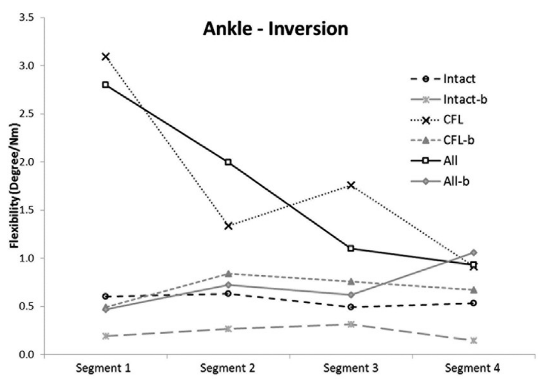
	Int		
Int+b	NS		
CFL	0.038	CFL	
CFL+b	-	NS	
All cut	0.028	NS	All
All+b	-	-	0.008

Segment 3

	Int		
Int+b	NS		
CFL	0.015	CFL	
CFL+b	-	NS	
All cut	0.008	NS	All
All+b	-	-	NS

Segment 4

	Int		
Int+b	NS		
CFL	NS	CFL	
CFL+b	-	NS	
All cut	0.021	NS	All
All+b	-	-	NS



B

Segment 1

	Int		
Int+b	0.008		
CFL	0.008	CFL	
CFL+b	-	0.008	
All cut	0.008	NS	All
All+b	-	-	0.008

Segment 2

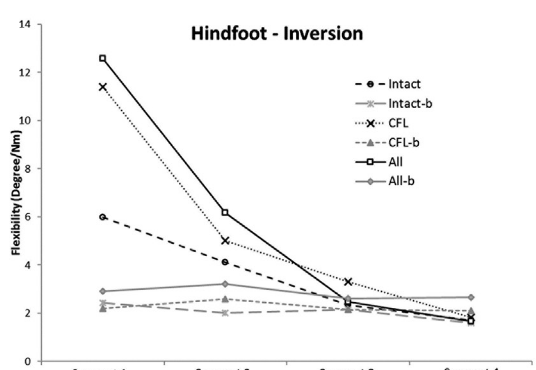
	Int		
Int+b	0.008		
CFL	NS	CFL	
CFL+b	-	0.015	
All cut	NS	NS	All
All+b	-	-	0.011

Segment 3

Friedman's test
p = 0.452

Segment 4

Friedman's test
p = 0.087



C

Fig. 3. Comparison of the subtalar (A), ankle (B) and ankle joint complex (C) joints mean segmental flexibility values in inversion for the intact condition (Int), intact with brace condition (Int + b), calcaneofibular ligament sectioned condition (CFL), CFL sectioned with a brace (CFL + b), additional sectioning of the cervical and interosseous talocalcaneal ligament (All cut) and All ligaments cut with a brace (All + b). The p-values of the Wilcoxon test are displayed in the matrices. NS means not significant and – means the test was not done for this pair.

Segment 1

	Int		
Int+b	0.021		
CFL	NS	CFL	
CFL+b	-	0.008	
All cut	NS	NS	All
All+b	-	-	0.011

Segment 2

	Int		
Int+b	0.008		
CFL	NS	CFL	
CFL+b	-	0.011	
All cut	NS	NS	All
All+b	-	-	0.011

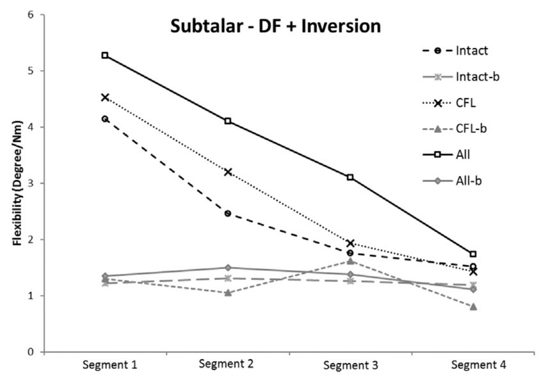
Segment 3

	Int		
Int+b	NS		
CFL	NS	CFL	
CFL+b	-	NS	
All cut	NS	NS	All
All+b	-	-	0.011

Segment 4

	Int		
Int+b	NS		
CFL	NS	CFL	
CFL+b	-	0.008	
All cut	NS	NS	All
All+b	-	-	NS

A



Segment 1

	Int		
Int+b	NS		
CFL	0.028	CFL	
CFL+b	-	0.038	
All cut	NS	NS	All
All+b	-	-	NS

Segment 2

	Int		
Int+b	0.011		
CFL	NS	CFL	
CFL+b	-	NS	
All cut	NS	NS	All
All+b	-	-	NS

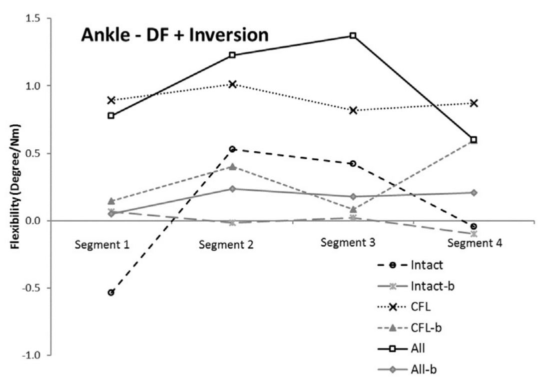
Segment 3

	Int		
Int+b	NS		
CFL	NS	CFL	
CFL+b	-	NS	
All cut	NS	NS	All
All+b	-	-	0.028

Segment 4

	Int		
Int+b	NS		
CFL	0.008	CFL	
CFL+b	-	NS	
All cut	NS	NS	All
All+b	-	-	NS

B



Segment 1

	Int		
Int+b	0.015		
CFL	NS	CFL	
CFL+b	-	0.011	
All cut	NS	NS	All
All+b	-	-	0.011

Segment 2

	Int		
Int+b	0.008		
CFL	0.038	CFL	
CFL+b	-	0.011	
All cut	NS	NS	All
All+b	-	-	0.011

Segment 3

	Int		
Int+b	NS		
CFL	NS	CFL	
CFL+b	-	0.008	
All cut	0.038	NS	All
All+b	-	-	0.008

Segment 4

	Int		
Int+b	NS		
CFL	0.011	CFL	
CFL+b	-	0.008	
All cut	0.038	NS	All
All+b	-	-	0.028

C

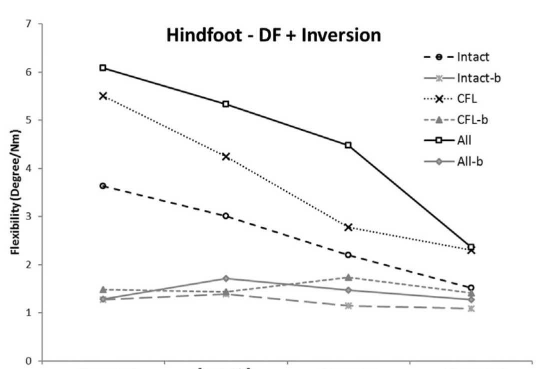


Fig. 4. Comparison of the subtalar (A), ankle (B) and hindfoot (C) joints mean segmental flexibility values in inversion with the foot placed in maximum dorsiflexion for the intact condition (Int), intact with brace condition (Int + b), calcaneofibular ligament sectioned condition (CFL), CFL sectioned with a brace (CFL + b), additional sectioning of the cervical and interosseous talocalcaneal ligament (All cut) and All ligaments cut with a brace (All + b). The p-values of the Wilcoxon test are displayed in the matrices. NS means not significant and – means the test was not done for this pair.

Segment 1

	Int		
Int+b	0.008		
CFL	0.028	CFL	
CFL+b	-	0.008	
All cut	NS	NS	All
All+b	-	-	0.021

Segment 2

	Int		
Int+b	0.008		
CFL	NS	CFL	
CFL+b	-	0.011	
All cut	NS	NS	All
All+b	-	-	0.011

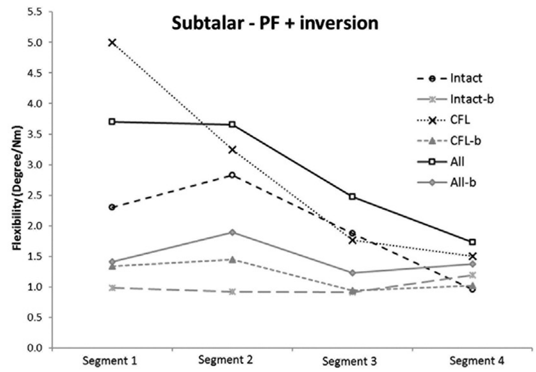
Segment 3

	Int		
Int+b	0.028		
CFL	NS	CFL	
CFL+b	-	0.038	
All cut	NS	NS	All
All+b	-	-	NS

Segment 4

Friedman's test
p = 0.063

A



Segment 1

	Int		
Int+b	0.038		
CFL	NS	CFL	
CFL+b	-	NS	
All cut	NS	NS	All
All+b	-	-	0.015

Segment 2

	Int		
Int+b	0.015		
CFL	NS	CFL	
CFL+b	-	0.015	
All cut	0.038	NS	All
All+b	-	-	NS

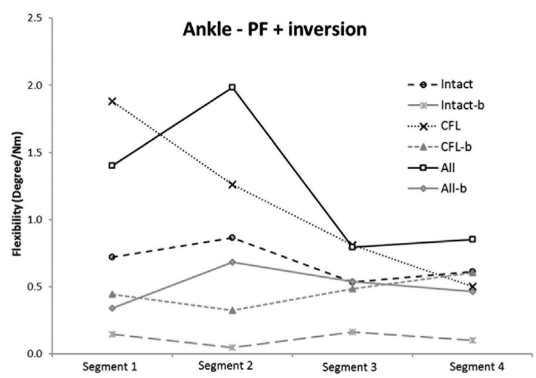
Segment 3

Friedman's test
p = 0.062

Segment 4

	Int		
Int+b	NS		
CFL	NS	CFL	
CFL+b	-	NS	
All cut	NS	NS	All
All+b	-	-	NS

B



Segment 1

	Int		
Int+b	0.008		
CFL	0.011	CFL	
CFL+b	-	0.008	
All cut	NS	NS	All
All+b	-	-	0.021

Segment 2

	Int		
Int+b	0.008		
CFL	NS	CFL	
CFL+b	-	0.008	
All cut	NS	NS	All
All+b	-	-	0.011

Segment 3

	Int		
Int+b	0.021		
CFL	NS	CFL	
CFL+b	-	0.011	
All cut	NS	NS	All
All+b	-	-	NS

Segment 4

	Int		
Int+b	NS		
CFL	NS	CFL	
CFL+b	-	NS	
All cut	NS	NS	All
All+b	-	-	NS

C

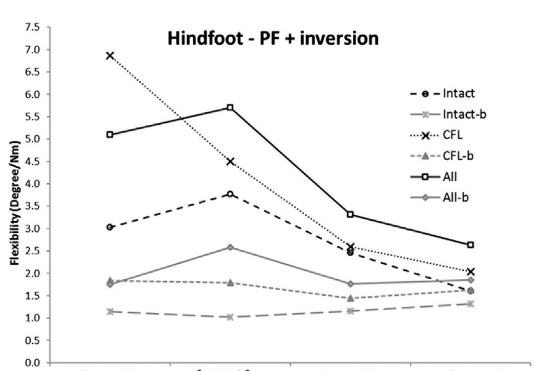


Fig. 5. Comparison of the subtalar (A), ankle (B) and hindfoot (C) joints mean segmental flexibility values in inversion with the foot placed in maximum plantarflexion for the intact condition (Int), intact with brace condition (Int + b), calcaneofibular ligament sectioned condition (CFL), CFL sectioned with a brace (CFL + b), additional sectioning of the cervical and interosseous talocalcaneal ligament (All cut) and All ligaments cut with a brace (All + b). The p-values of the Wilcoxon test are displayed in the matrices. NS means not significant and – means the test was not done for this pair.

Segment 1

	Int		
Int+b	0.038		
CFL	NS	CFL	
CFL+b	-	0.008	
All cut	NS	NS	All
All+b	-	-	0.028

Segment 2

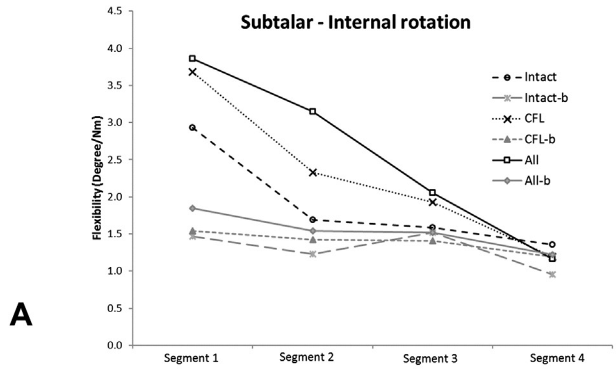
Friedman's test
p = 0.077

Segment 3

Friedman's test
p = 0.209

Segment 4

Friedman's test
p = 0.94



Segment 1

	Int		
Int+b	NS		
CFL	NS	CFL	
CFL+b	-	NS	
All cut	NS	NS	All
All+b	-	-	0.038

Segment 2

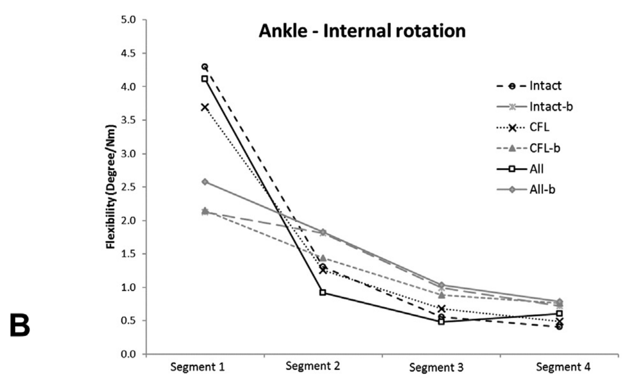
	Int		
Int+b	0.008		
CFL	NS	CFL	
CFL+b	-	0.008	
All cut	NS	NS	All
All+b	-	-	0.021

Segment 3

	Int		
Int+b	NS		
CFL	NS	CFL	
CFL+b	-	NS	
All cut	NS	NS	All
All+b	-	-	0.008

Segment 4

	Int		
Int+b	NS		
CFL	NS	CFL	
CFL+b	-	NS	
All cut	NS	NS	All
All+b	-	-	NS



Segment 1

	Int		
Int+b	0.011		
CFL	NS	CFL	
CFL+b	-	0.008	
All cut	NS	NS	All
All+b	-	-	0.015

Segment 2

Friedman's test
p = 0.18

Segment 3

Friedman's test
p = 0.829

Segment 4

Friedman's test
p = 0.946

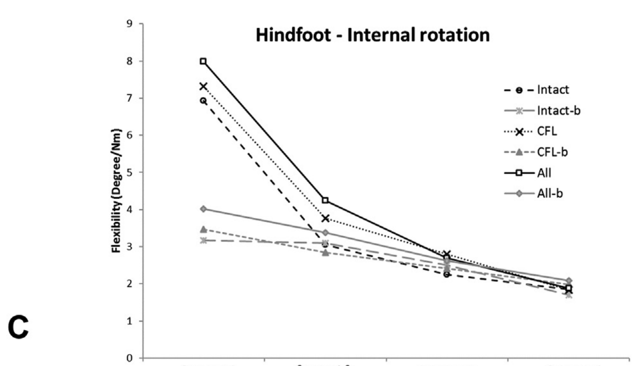


Fig. 6. Comparison of the subtalar (A), ankle (B) and hindfoot (C) joints mean segmental flexibility values in internal rotation for the intact condition (Int), intact with brace condition (Int + b), calcaneofibular ligament sectioned condition (CFL), CFL sectioned with a brace (CFL + b), additional sectioning of the cervical and interosseous talocalcaneal ligament (All cut) and All ligaments cut with a brace (All + b). The p-values of the Wilcoxon test are displayed in the matrices. NS means not significant and – means the test was not done for this pair.

the CFL was sectioned in isolation (Choisne et al., 2013) or in combination with the anterior talofibular ligament (ATFL) (Ringleb et al., 2005; Rosenbaum et al., 1998). This finding suggests that instability at the subtalar joint after sectioning of the CFL occurs in the early stage of inversion which then is reduced with the foot moving to the end range of inversion. Bony structure as well as the intrinsic ligaments might help in restricting subtalar joint flexibility at the subtalar joint at the end range of inversion (Leardini et al., 2001). Other motion applied to the foot such as supination, described as the motion around the subtalar joint axis, might increase after CFL sectioning and lead to a more unstable subtalar joint. Future studies should investigate the effect of CFL sectioning on the subtalar joint flexibility and end range of motion during supination.

Looking at the flexibility at the ankle during inversion, sectioning the CFL increased flexibility in segment 1, 2 and 3 which is in agreement with kinematics results showing a significant increase in the end range of inversion compared to the intact foot (Choisne et al., 2017; Choisne et al., 2013). Additional sectioning of the intrinsic ligaments increased late flexibility at the ankle in inversion meaning that the ankle might not have the appropriate bony structure limiting ankle inversion (Leardini et al., 1999). The present study may help enlighten the existing conflict on the role of the CFL ligament in ankle and subtalar joints stability (Cass et al., 1984; Choisne et al., 2012; Hollis et al., 1995; Kjaersgaard-Andersen et al., 1987; Laurin et al., 1968; Leonard, 1949; Martin et al., 2002; Ringleb et al., 2005; Rosenbaum et al., 1998; Weindel et al., 2010). As shown in this study, the CFL limits early inversion flexibility at the subtalar joint which is then constrain by the intrinsic ligaments and bony structure while the ankle joint, considered as a hinge joint, does not hold the necessary bony structure to constrain inversion flexibility and rely on lateral ligaments exclusively. When the foot is held in maximum dorsiflexion, the talus is constrained in the ankle mortise which explains why ankle flexibility only increased in the early stage after sectioning the CFL and did not change after additional sectioning of the intrinsic ligaments. A previous in vitro flexibility study (Lapointe et al., 1997) found a large statistically significant increase in early hindfoot flexibility after sectioning the CFL during inversion with late flexibility not being affected by resection of the ligament. However the ankle and subtalar joints were not differentiated which make it difficult to compare with the present study. To our knowledge, this is the only study that investigated the flexibility characteristics at the subtalar and ankle joints after sectioning the CFL alone and in combination to the intrinsic ligaments during applied inversion and internal rotation.

The second purpose of this study was to investigate the effect of a semi-rigid ankle brace on the ankle and subtalar joints flexibility after instability was created at the hindfoot. The semi-rigid ankle brace restricted segment 1 and 2 flexibility at the hindfoot during inversion independently of the foot sagittal position and ligaments condition. Cadaver studies displayed a significant restriction in motion by using ankle stabilizer devices after ligament injuries. For example, a significant decrease in talar tilt and anterior drawer was measured after applying a brace on specimen with ATFL and CFL deficiencies (Bruns and Staerk, 1992). A previous study from the same authors (Choisne et al., 2013) showed that the same ankle brace reduced inversion ROM for all joints with a decrease of 26%, 34% and 40% in the intact hindfoot when the foot was placed in neutral, dorsi- and plantarflexion respectively which is in accordance with the flexibility results found in the present study. In the present study, the largest effects of the ankle brace occurred during early flexibility which means near the neutral position of the foot. In this 'neutral zone' the ankle joint complex is known to be very flexible while toward the end range of motion the hindfoot tends to become stiffer (Siegler et al., 1988). The ankle brace contribution to reduce flexibility in this 'neutral zone' at the hindfoot was significant which is the most vulnerable zone at the ankle joint complex during the loading response, when the ankle joint complex tends to give way. The same conclusion were drawn in a previous study measuring the flexibility of the ankle complex on 10 healthy subjects (Siegler et al., 1997). After testing ankle-complex flexibility on four different ankle braces in 10 healthy subjects in inversion/eversion and internal/external rotation, each brace provided significant support in inversion and internal rotation to the ankle joint complex (i.e., the calcaneus relative to the tibia) with the active ankle brace demonstrating the best reduction in flexibility (Siegler et al., 1997). The present study showed that the semi-rigid ankle brace reduced flexibility at all joints for all ligament conditions during inversion however this decrease in flexibility was significant only in the 'neutral zone' and mostly at the subtalar joint. Inversion mostly happens at the subtalar joint which makes this joint very flexible while the ankle joint demonstrated a reduced range of motion when inversion was applied to the foot (Choisne et al., 2013). This could explain the low reduction in flexibility happening at the ankle during inversion. The same conclusion could be drawn during internal rotation where we observed an increase in ankle segment 2 to 4 flexibility with the brace worn. The present study showed that brace does have a significant effect on the flexibility on both the ankle and subtalar joints in inversion, which may mean that as the flexibility of the joints increase due to the lack of ligaments, the brace is providing a substitute external source of stability for the joints. The consistent levels of flexibility between all conditions and segments of motion while the brace is applied can allow the conclusion that the brace becomes a stability structure regardless of the ligament condition. Although previous studies have shown ankle braces to limit range of motion, additional research would be required to determine if limitation in the end range of motion is sufficient to determine if the ankle brace is efficient for re-injury prevention or if we need additional information on the flexibility change caused by the brace especially in the neutral zone.

Limitations of our study include the cadaveric nature used to reproduce physiological conditions. For example, the present study applied a 4 Nm inversion moment and 3.8 Nm internal moment which might be too painful for a living person to sustain. Moreover, after applying a 3.4 Nm inversion moment on cadaver feet and on living individuals through an MRI a 3° higher range of inversion was noticed in vitro at the ankle with a similar subtalar joint rotation (Siegler et al., 2005). Another limitation was the use of an open kinetic chain device. People wear ankle braces in a closed kinetic chain condition and therefore might demonstrate different flexibility behavior. A future study should look at the differences in kinematics and flexibility using a closed kinetic chain apparatus. Also, this study looked at the passive inversion and internal rotation motion while braces are used in more dynamic conditions which might not be pure inversion or pure internal rotation but a combination of both motion. The last limitation is the non-uniform speed used to apply rotation to the foot. When dividing the force-displacement curves into 4 segments we assumed that we applied motion to the foot in a uniform speed which was not always the case as motion was applied manually. Future studies might want to add motors to apply a uniform speed to the foot through the range of motion.

The results of this study suggest that sectioning the CFL increased early subtalar flexibility while bony structures might be responsible for limiting inversion end range of motion. Therefore inversion might not be a good motion to study instability at the subtalar joint. Supination, combination of inversion, internal rotation and plantarflexion of the foot, is known to describe motion around the subtalar joint axis and might be more suitable to study flexibility and instability at the subtalar joint. In addition, the study demonstrated the importance of evaluating the passive support provided by ankle braces based on their effect on the subtalar and ankle joint flexibility as well as their end range of motion restriction.

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Conflict of interest

The authors have no conflicts of interest to report.

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