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Hinged ankle braces do not alter knee mechanics during sidestep cutting

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ABSTRACT

Lateral ankle sprains are common injuries in quick, dynamic movements and are caused by rapid ankle inversion. Ankle braces are used to reduce ankle inversion, while allowing normal plantar and dorsiflexion ranges of motion. Knee injuries, such as anterior cruciate ligament injuries, are also common in dynamic movements. It is important to understand how ankle braces affect injury risk at other proximal joints. There is limited and conflicting results on how ankle braces affect knee mechanics during these types of movements. Additionally, it is unknown if sex differences exist when using an ankle brace. Therefore, the purpose of this study was to determine the effects of a hinged ankle brace and sex during a 45° cutting movement. Three-dimensional kinematics and ground reaction forces were collected using a motion capture system and force plate on ten men and eight women during cutting trials. 2×2 repeated measures ANOVAs were used to detect differences in ground reaction forces, as well as knee and ankle kinematics between brace conditions and sex ($p < 0.05$). The brace condition exhibited greater initial contact ankle dorsiflexion ($p = 0.011$), decreased peak ankle inversion ($p < 0.01$), and increased vertical loading rate ($p = 0.040$). Females performed the cutting movement with less initial contact ($p = 0.019$) and peak knee flexion ($p = 0.023$) compared to males. Ankle bracing had no impact on the observed sex differences. Females exhibited decreased knee flexion compared to males, which has been well documented in the literature. The use of an ankle braces reduced ankle injury risk variables while not adversely impacting knee mechanics during a 45° sidecutting movement.

1. Introduction

Lower extremity injuries account for over 50% of reported injuries during athletics events (Hootman et al., 2007), with a majority of these injuries occurring at the ankle, followed by the knee (Fong et al., 2007). For the ankle-foot complex, approximately 85% of injuries are classified as lateral ankle sprains, making the lateral ligament complex the most frequently injured structure in the body (Garrick, 1977). This lateral sprain is caused by rapid inversion combined with plantarflexion of the ankle, which can occur during dynamic movements, such as cutting maneuvers, that are poorly executed with an abnormal foot placement (Garrick, 1977). At the knee, meniscal and ligamentous injuries are common occurrences (Hootman et al., 2007). Specifically, noncontact anterior cruciate ligament (ACL) injuries that occur during dynamic movements, such as planting and cutting (Nagano et al., 2009), are among the most common ligamentous knee injury requiring surgery (Griffin et al., 2006). Cadaver studies have shown that large shear forces, a knee near full extension, frontal plane loading, and high tibial rotation excessively load the ACL, placing it at an increased risk of injury (Fukuda et al., 2003; Markolf et al., 1995).

The overall goal of an ankle brace used in athletics is to reduce ankle inversion, while still being able to maintain normal plantar and dorsiflexion. Allowing a greater sagittal plane range of motion (ROM) at the ankle has the potential to decrease injury risk at other joints due to subsequent increases in hip and knee joint sagittal plane ROMs, as well as overall decreases in ground reaction forces (GRF) and vertical loading rates (VLR) due to a "softer" landing (Butler et al., 2003; Devita and Skelly, 1992; Zhang et al., 2000). Softer landings allow 19% more kinetic energy to be absorbed by muscular tissue due to increased ROM, thus reducing the stress experienced by non-muscular tissue such as the ACL (Devita and Skelly, 1992). Several types of ankle braces are available for commercial use, such as lace-up, Aircast, and hinged-style ankle braces, each with their own stabilizing effects. The use of hinged ankle braces has become common in preventing lateral ankle sprains in athletics and has been shown to decrease the incidences of ankle injury in collegiate volleyball players (Pedowitz et al., 2008). This type of brace allows for free sagittal plane rotation at the ankle,

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resulting in a greater sagittal ROM (i.e. softer landing), while restricting frontal plane movement at the ankle, and has also been recommended for use in dynamic activities (Eils et al., 2002).

However, while the use of ankle braces has been shown to prevent ankle injuries, it is important to have a thorough understanding of how ankle bracing affects injury risk at more proximal joints, such as the knee. If ankle braces decrease the risk of injury at one joint but increase the risk of injury at another joint, their use would be inappropriate. While epidemiological studies have examined the effects of ankle brace use on injury rates (McGuine et al., 2011; McGuine et al., 2012), there are limited and conflicting results regarding how ankle braces biomechanically affect knee mechanics during dynamic tasks (Mason-Mackay et al., 2016a). The tasks used in previous research have also varied, including both landing and cutting tasks, making comparisons of the results challenging. While some research has found that lace-up braces do not alter knee flexion ROM and subsequently knee joint loading (Greene et al., 2014), other research has found that hinged ankle braces may potentially increase the risk of knee injury due to increased knee internal rotation angle (Klem et al., 2017; Santos et al., 2004), a main risk factor in ACL injury (Markolf et al., 1995).

There are also inconsistencies when it comes to how an ankle brace affects peak GRF and VLR of the lower extremity. While some studies have found no differences in peak vertical GRF and knee loading (Greene et al., 2014; Mason-Mackay et al., 2016b; Vanwanseele et al., 2014), others have found that differences do exist. Sacco Ide et al. (2006) saw that an Aircast-type brace decreased peak vertical GRF over a longer period, which decreased VLR experienced in the lower extremity. It is important to note that joint mechanics have an influence on loading rates of the lower extremity. Specifically, reduced ankle and knee flexion ROMs during a landing has been found to significantly increase the load experienced at the knee and may be associated to certain injuries, such as patellar tendinopathy (Bisseling et al., 2008) and stress fractures (Butler et al., 2003).

Additionally, it is not known if a sex effect exists during dynamic tasks, such as cutting, when an ankle brace is present. In general, females have been found to be 2–7 times more likely to experience an ACL injury in athletics (Agel et al., 2005). Furthermore, sex differences exist in cutting maneuvers, with females exhibiting significantly greater injury risk compared to males (Agel et al., 2005; McLean et al., 2005b). Females consistently display decreased knee flexion angles, as well as increased knee abduction angles, during cutting maneuvers, which can significantly increases the load on the ACL and increases risk of injury (Markolf et al., 1995). Interestingly, while females tend to land in a more erect position due to decreased knee flexion, no differences have been seen in vertical GRF variables between males and females, indicating possible differences in energy absorption patterns between the sexes (Decker et al., 2003). Unfortunately, there is limited research on the effects of an ankle brace on sex differences during a cutting task that must be examined.

While previous research has examined the effects of ankle bracing on joint kinematics and ACL loading during different tasks, such as cutting, no study to date has examined sex differences with ankle bracing regarding these variables during a cutting task. Therefore, the purpose of this study was to determine the effects of an Ultra Zoom® hinged ankle brace and sex on the three-dimensional kinematics of the ankle and knee, GRF, and vertical loading rate (VLR) during a 45° cutting maneuver. Firstly, it was hypothesized that the brace condition would decrease frontal plane ankle movement while not affecting sagittal plane movement and would have no effect on knee kinematic injury risk variables. Secondly, it was hypothesized that the brace condition would decrease GRF and VLR. Lastly, it was hypothesized that females would exhibit increased injury risk variables compared to males.

2. Materials & methods

2.1. Participants

Prior to data collection, ethical approval was received from the University's Institutional Review Board. Ten males (height: 1.81 ± 0.07 m, mass: 85.43 ± 10.20 kg) and eight females (height: 1.66 ± 0.03 m, mass: 68.07 ± 5.61 kg) who were healthy and recreationally active volunteered for the study. An a priori power analysis was conducted using G*Power 3.1.9.2 (Faul et al., 2007) to identify the appropriate sample size for a 2 × 2 (sex × brace condition) repeated measures ANOVA. It was determined that 16 participated (8 per group) would be needed to achieve 80% power at a statistical significance criterion of 0.05, with a large effect size (Cohen's $f = 0.4$). Additional participants were collected in case of potential failure to complete the tasks. Upon arrival, all participants received a full explanation of the study purpose and procedures. Prior to data collection, participants provided written informed consent in accordance with University Institutional Review Board policies. Recreationally active was defined as performing at least 30 min of exercise three or more times a week. Participants completed a general medical history questionnaire that was used to describe the study sample. Individuals who reported a lower extremity injury in the past six months, any history of lower extremity surgery, or a health condition which may have affected their ability to complete the experimental task were excluded from participation. Spandex shorts and lab standard tennis shoes (Air Max Glide, Nike, Beaverton, OR, USA) were provided for testing sessions.

2.2. Instruments

Three-dimensional marker coordinate data were collected at 200 Hz using an eight-camera Vicon MX motion analysis system (Vicon, Centennial, CO, USA). GRF were measured synchronously at 2000 Hz using two flush mounted force plates (Bertec, Columbus, OH, USA). Single reflective markers were placed bilaterally on the acromioclavicular joints, iliac crests, greater trochanters, medial and lateral knee epicondyles, medial and lateral malleoli, first metatarsal heads, and fifth metatarsal heads (Fig. 1). Marker tracking in movement trials utilized rigid cluster plates with four retro-reflective markers positioned on the upper torso and pelvis, as well as, bilateral thighs, shanks, and feet. A static calibration trial was collected with all markers in place. For individual participant calibration, the participant stood with arms crossed high over the chest and each foot on a separate force plate. Calibration-only markers were then removed, leaving the cluster markers in place.

2.3. Procedures

Participants then completed 45° sidestep cutting trials with and without an Ultra Zoom® ankle brace (Ultra Athlete, LLC., Carmel, IN, USA) on their dominant foot, defined as their preferred kicking leg. All trials were performed with an approach speed of 4.5–5.0 $m \cdot s^{-1}$, monitored using two infrared photocell switches (Model 63501-IR, Lafayette Instrument, IN) spaced 2 m apart and a digital timer (Model 54035-A, Lafayette Instruments, Lafayette, IN). After striking the force plate, participants were instructed to cut to the contralateral side along a 1 m wide path oriented at 45° to the line of progression, which ensured a cutting angle of 40–50°. A successful trial was defined as one during which approach speed was

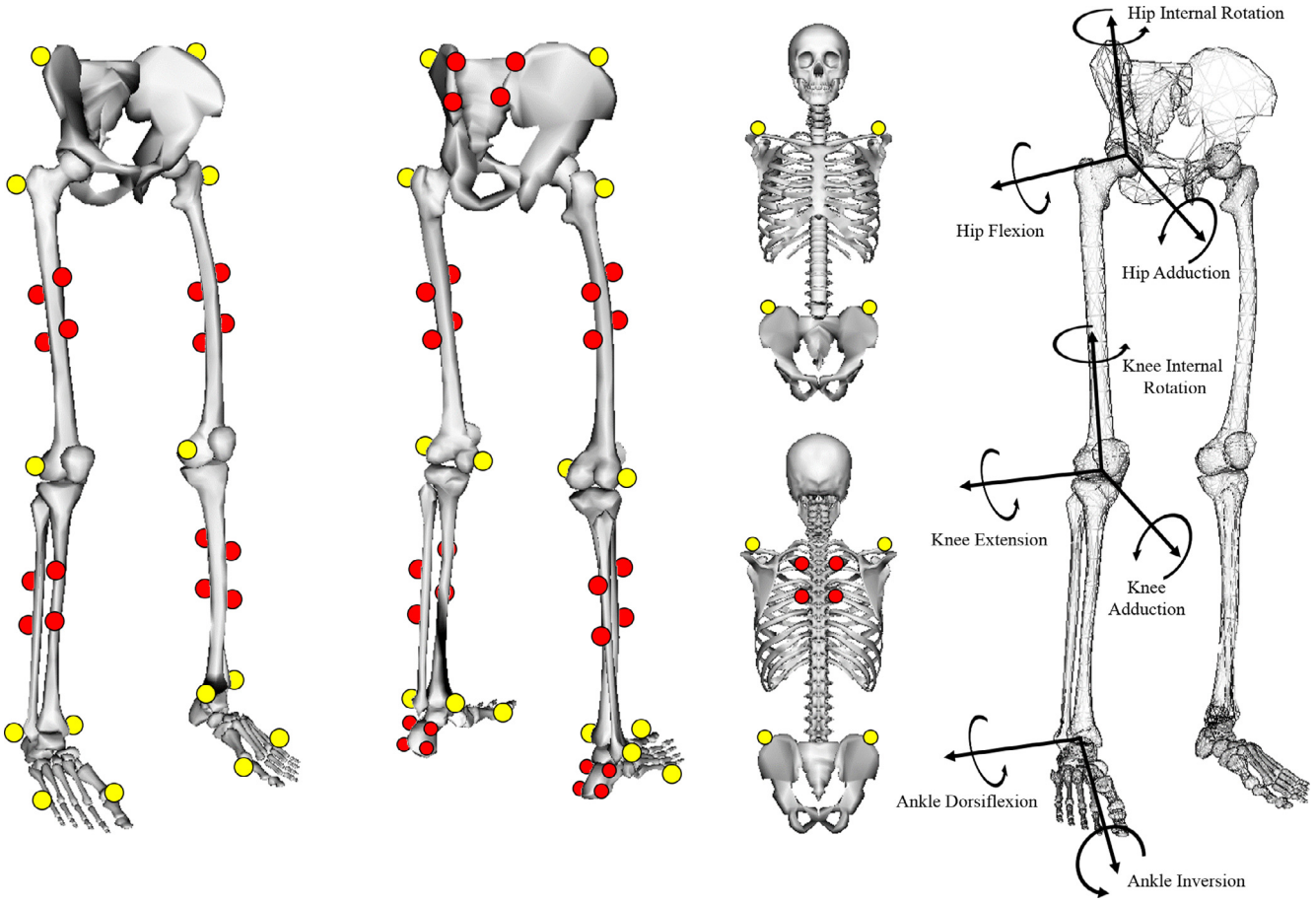

Fig. 1. Marker placement used to define the kinematic model. Anatomical markers (yellow) were used to define joint centers and were removed prior to data collection. Cluster markers (red) were used to track segment movement during data collection. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

maintained, participants' entire dominant foot came in contact with the force plate, and they stayed in the 1 m wide path. Five successful trials of each condition were recorded and the order of condition (brace, no brace) was counterbalanced between participants.

2.4. Data processing

Raw three-dimensional marker coordinate and ground reaction force data were low-pass filtered using a fourth-order, zero lag, recursive Butterworth filter with a cutoff frequency of 10 Hz (Kristianslund et al., 2012) in Visual3D (v6.00, C-Motion Inc., Rockville, MD). A kinematic model comprised of eight skeletal segments (trunk, pelvis, and bilateral thighs, shanks, and feet) was created from the standing calibration trial. Hip joint centers were placed 25% of the distance from ipsilateral to contralateral greater trochanter markers (Weinhandl and O'Connor, 2010). Knee joint centers were the midpoint between femoral epicondyle markers (Grood and Suntay, 1983), and ankle joint centers were the midpoint between malleoli markers (Wu et al., 2002). Three-dimensional hip, knee, and ankle angles were then calculated using a joint coordinate system approach (Grood and Suntay, 1983).

2.5. Statistical analysis

Discrete kinematic and ground reaction force variables during the stance phase were identified to evaluate differences between brace conditions in males and females performing the sidestep cut. The stance phase was defined as the time from initial contact (IC) to toe-off, which were identified using a vertical ground reaction force threshold of 10 N. These variables included initial contact and peak knee flexion, knee abduction, knee internal rotation, ankle dorsiflexion and ankle inversion angles. Peak vertical, posterior and medial ground reaction forces were also identified and normalized to body weight. Finally, VLR was calculated by dividing the peak vertical force by the time to peak value ($BW \cdot s^{-1}$). Separate 2×2 (sex $\times$ brace condition) repeated measures ANOVAs were used to detect between-subjects (sex) and within-subjects (brace condition) main effects for all dependent variables. All data were analyzed using SPSS (v. 24, SPSS Inc., Chicago, IL), with an alpha level set to $p \leq 0.05$.

3. Results

The means and standard deviations for GRF, IC joint angles and peak joint angles are presented in Table 1. Mean ensemble time-series for significant kinematic variables are presented in Fig. 2. Significant brace condition differences were found for IC ankle dorsiflexion angle ($F_{1,16} = 8.176$. $p = 0.011$, $\eta^2 = 0.338$), peak ankle inversion angle ($F_{1,16} = 22.442$, $p < 0.001$, $\eta^2 = 0.584$), and VLR ($F_{1,16} = 4.972$, $p = 0.040$, $\eta^2 = 0.237$). Participants demonstrated 3.4° greater IC ankle dorsiflexion, 5.7° less peak ankle inversion, and 2.15 $BW \cdot s^{-1}$ greater VLR in the brace condition compared to the no brace condition during the cutting maneuver. Significant sex differences were found for IC knee flexion angle ($F_{1,16} = 6.790$, $p = 0.019$, $\eta^2 = 0.298$) and peak knee flexion angle ($F_{1,16} = 6.367$, $p = 0.023$, $\eta^2 = 0.285$). Females demonstrated 7.0° less IC knee flex-

Table 1
Mean ± SD ground reaction force (GRF), vertical loading rate (VLR), and 3D knee and ankle initial contact (IC) angles and peak angles of two brace conditions during a 45° cutting movement.

		Brace		No brace		Int.	Brace	Sex
		Male	Female	Male	Female	*p*	*p*	*p*
GRF	Peak Medial (BW)	−0.84 ± 0.15	−0.87 ± 0.14	−0.84 ± 0.14	−0.92 ± 0.18	0.174	0.226	0.439
	Peak Posterior (BW)	−0.94 ± 0.21	−1.04 ± 0.14	−0.92 ± 0.24	−1.03 ± 0.14	0.768	0.656	0.247
	Peak Vertical (BW)	2.38 ± 0.27	2.57 ± 0.27	2.31 ± 0.30	2.57 ± 0.33	0.468	0.414	0.108
	VLR ($BW \cdot s^{-1}$)*	48.01 ± 7.38	50.77 ± 7.56	45.07 ± 7.92	49.43 ± 9.28	0.420	0.040	0.348
IC	Knee Flexion (°)§	−21.3 ± 6.0	−14.7 ± 6.9	−22.4 ± 5.5	−15.0 ± 6.1	0.753	0.523	0.019
	Knee Abduction (°)	−0.3 ± 3.8	−3.1 ± 4.8	0.4 ± 2.1	−3.3 ± 4.7	0.408	0.654	0.086
	Knee Int Rot (°)	−4.4 ± 4.9	−8.4 ± 7.5	−6.6 ± 5.8	−7.6 ± 5.6	0.158	0.515	0.362
	Ankle Dorsiflexion (°)*	−0.6 ± 10.8	5.3 ± 4.5	−4.7 ± 11.8	2.6 ± 9.0	0.571	0.011	0.158
	Ankle Inversion (°)	7.4 ± 3.3	7.3 ± 6.2	6.1 ± 6.3	7.9 ± 7.1	0.393	0.760	0.754
Peak	Knee Flexion (°)§	−60.3 ± 7.5	−53.4 ± 7.1	−60.4 ± 7.5	−51.9 ± 5.2	0.552	0.593	0.023
	Knee Abduction (°)	−6.0 ± 5.8	−9.9 ± 4.9	−5.5 ± 4.7	−9.2 ± 5.7	0.906	0.303	0.138
	Knee Int Rot (°)	2.3 ± 4.8	−0.7 ± 4.2	2.4 ± 3.6	−0.9 ± 6.4	0.872	0.925	0.157
	Ankle Dorsiflexion (°)	17.8 ± 5.8	17.0 ± 4.8	15.5 ± 7.4	17.6 ± 4.3	0.402	0.620	0.765
	Ankle Inversion (°)*	20.6 ± 5.7	22.8 ± 6.5	25.8 ± 6.9	28.9 ± 7.9	0.694	0.000	0.385

* Significant brace effect ($p < 0.05$).
§ Significant sex effect ($p < 0.05$).

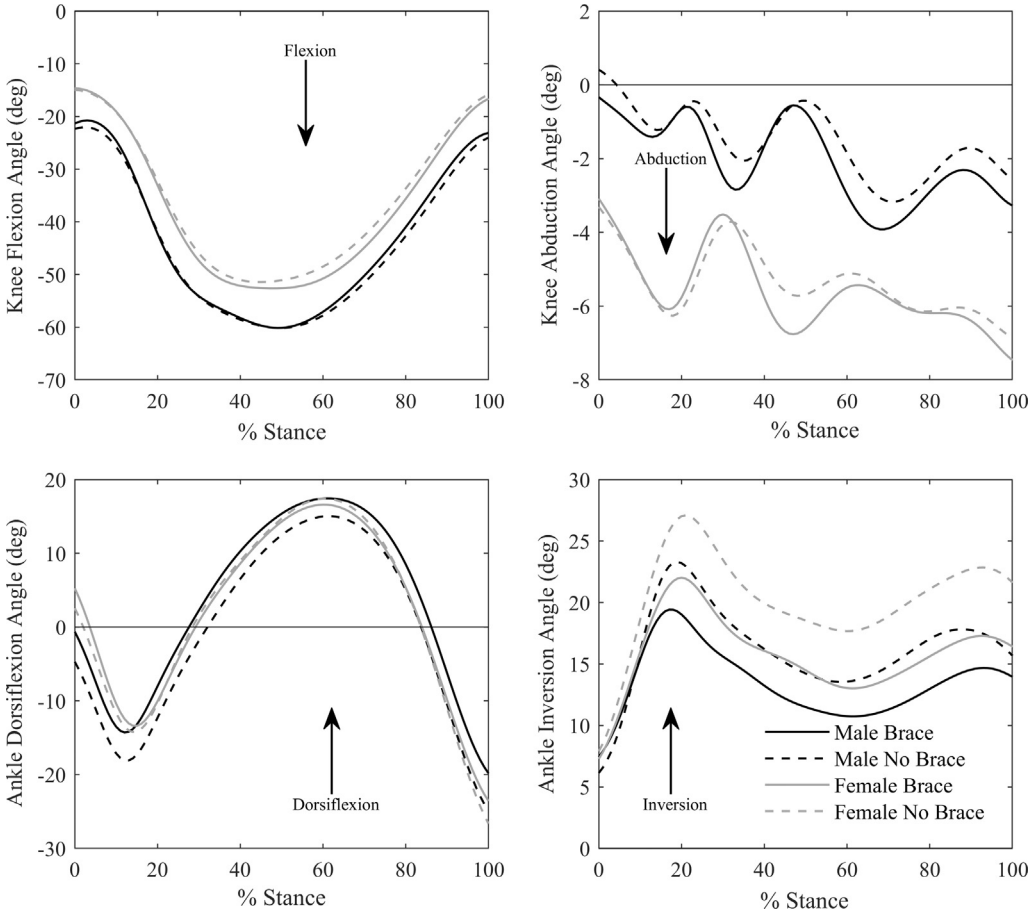

Fig. 2. Mean knee and ankle joint angles during the stance phase of a 45° sidecutting movement with an ankle brace (solid lines) and without an ankle brace (dashed lines) of males (black lines) and females (gray lines). Positive values indicate hip knee extension/adduction, and ankle dorsiflexion/inversion joint rotations.

ion, as well as 7.7° less peak knee flexion compared to males during the cutting maneuver. No other significant differences were found.

4. Discussion

The purpose of this study was to determine the effects of an Ultra Zoom® hinged ankle brace and sex on three-dimensional kinematics of the ankle and knee, GRF, and VLR during a 45° cutting maneuver. Initial contact ankle dorsiflexion was greater in the brace condition, and peak ankle inversion was decreased in the brace condition, which partially supports our first hypothesis. VLR was significantly greater in the brace condition compared to the no brace condition, which is not in agreement with our second hypothesis. Finally, females exhibited both decreased initial con-

tact and peak knee flexion angles compared to males, which supports our third hypothesis.

Lateral ankle sprains are common in sports such as soccer, basketball and volleyball (Hootman et al., 2007; Quinn et al., 2000). Ankle braces are used in these types of sports to reduce the occurrence of lateral ankle sprains by restricting ankle inversion without limiting athletic performance (Eils et al., 2002). Unfortunately, performance could become impaired if the functional dorsiflexion ROM is reduced, which has been found to be common in braced ankles during acute bouts of dynamic tasks (Bot and van Mechelen, 1999).

Not only could reducing dorsiflexion ROM impair performance, but it could also increase ACL injury risk. Fong et al. (2011) found significant correlations between increased dorsiflexion ROM, greater sagittal-plane displacements, and decreased landing forces, suggesting that dorsiflexion ROM may potentially decrease ACL loading, thus decreasing injury risk. Previous research has also found that in unbraced ankles, when individuals land with both ankle inversion and plantarflexion, knee flexion ROM decreases, while knee abduction ROM increases (Valenzuela et al., 2016), both of which have been shown to increase ACL injury risk (Markolf et al., 1995; Nagano et al., 2009). While reduced dorsiflexion ROM has been shown to alter variables associated with increased ACL injury risk in unbraced ankles, there has been limited research on how ankle braces affect ACL injury risk. Therefore, it is important to identify if ankle bracing adversely affects the knee and puts it at an increased risk of injury.

The current study found that peak inversion angle was significantly reduced in the brace condition by 4.41°, which agrees with previous findings (Klem et al., 2017; Vanwanseele et al., 2014) and shows that the brace achieved its overall goal of reducing frontal plane motion. Initial contact dorsiflexion was also 3.46° greater in the braced condition, with no significant differences in peak dorsiflexion. These two findings show that the ankle brace achieved its overall goal of reducing frontal plane ankle motion while not impacting sagittal plane range of motion.

While peak vertical GRF was not significantly different between conditions, VLR was significantly greater in the brace condition. This increased VLR in the brace condition can be primarily attributed to differences observed in male participants, who exhibited a 2.94 $BW{\cdot}s^{-1}$ greater VLR between brace conditions, while females only exhibited a 1.34 $BW{\cdot}s^{-1}$ increase between conditions. Some level of stiffness is required during athletic activities to achieve optimal performance (McMahon and Cheng, 1990). However, vertical loading rate has been associated with an increased risk of overuse injuries, such as tibial stress fractures. Repeated excessive loading causes functional adaptations, leading to further overload, which will eventually result in tissue injury (Kibler, 1990). VLR is reportedly greater in runners who had previously sustained a tibial stress fracture, suggesting they were already exhibiting increased VLR prior to being injured (Hreljac et al., 2000; Milner et al., 2006). One might reasonably expect an ankle brace to increase joint stiffness due to frontal plane movement restriction, which is theorized to increase VLR and shock experience by the lower extremity, thus increasing the risk of bony injuries such as stress fractures (Butler et al., 2003). While there was an increase in VLR in the braced ankle compared to the unbraced ankle (49.24 $BW{\cdot}s^{-1}$ vs. 47.01 $BW{\cdot}s^{-1}$, respectively), the Ultra Zoom® ankle brace restricted frontal plane ankle motion and did not affect dorsiflexion ROM, as well as not impacting knee mechanics.

Compared to males, females exhibited a 7.0° decrease in initial contact knee flexion angle, as well as a 7.7° decrease in peak knee flexion angle during the 45° cutting maneuver as compared to males. This sex difference has been well documented in the literature (Malinzak et al., 2001; McLean et al., 2005b; Weinhandl et al., 2017). In general, ACL load is increased when the knee is more extended (Markolf et al., 1995). This increased load placed on the ligament increases the risk of ACL injury. While females exhibited decreased flexion angles, McLean et al. (2004) found that abnormalities in the sagittal plane alone do not apply enough load to the ACL to cause injury. Therefore, this difference alone between sexes does not appear to solely place females at an increased risk of ACL injury. It should be noted that, while not significantly different ($p = 0.086$), females exhibited IC knee abduction angles approximately 3° greater than their male counterparts. This finding is consistent with the literature which has consistently shown that females exhibit greater knee abduction angles compared to males in multiple athletic tasks such as sidestep and cross-over cutting (Malinzak et al., 2001; McLean et al., 2005a), unilateral and bilateral landing (Kernozek et al., 2005; Pappas et al., 2007), as well as land-and-cut maneuvers (Weinhandl et al., 2017). Increased knee abduction angles have been shown to increase the load placed on the ACL via computer simulation studies of unilateral landings (Shin et al., 2009) and sidestep cutting (Weinhandl et al., 2013). Increased knee abduction angles have also been prospectively identified as an ACL injury risk factor (Hewett et al., 2005), suggesting females in the current study may have experienced increased ACL loading and therefore been at increased risk of ACL injury. Our findings, taken with the results of these previous studies, support the hypothesis suggested by Kernozek et al. (2005) that a common mechanism for noncontact ACL injury in females may exist across a wide range of movements.

It is important when interpreting the results to acknowledge certain methodological limitations of the current study. First, participants wore the ankle brace only for the duration of the testing session. Therefore, possible effects of long-term ankle brace use were not assessed. Second, participants were required to wear a hinged ankle brace that they may not be familiar with wearing. Introducing this unfamiliar brace could have influenced movement patterns during testing. Finally, the variances in participants' physical characteristics, such as muscle strength and flexibility, might have some effect on the results. Participants were required to be recreationally active, so it was assumed that physical characteristics would be similar between participants.

5. Conclusions

The current study found that during a common dynamic task, the Ultra Zoom® ankle brace restricted frontal plane ankle movement while not affecting dorsiflexion ROM. Furthermore, the only significant changes in knee mechanics were due to sex differences, which has been well documented. These findings indicate that the use of this hinge brace is suitable for sports, reduces the risk of lateral ankle injuries, and does not alter knee mechanics, and therefore may not increase the risk of ACL injury.

Conflict of interest statement

The authors have no conflict of interest related to the present work to disclose.

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