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Research article

Acute Effects of Foot Rotation in Healthy Adults during Running on Knee Moments and Lateral-Medial Shear Force

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Abstract
As runners age, the likelihood of developing osteoarthritis (OA) significantly increases as 10% of people 55+ have symptomatic knee OA while 70% of people 65+ have radiographic signs of knee OA. The lateral-medial shear force (LMF) and knee adduction moment (KAM) during gait have been associated with cartilage loading which can lead to OA. Foot rotation during gait has been shown to alter the LMF and KAM, however it has not been investigated in running. The purpose of this study was to investigate changes in the KAM and LMF with foot rotation during running. Twenty participants volunteered and performed five running trials in three randomized conditions (normal foot position [NORM], external rotation [EXT], and internal rotation [INT]) at a running speed of 3.35m·s^{-1} on a 20 meter runway. Kinematic and kinetic data were gathered using a 9-camera motion capture system and a force plate, respectively. Repeated measures ANOVAs determined differences between conditions. The KAM and LMF were lower in both EXT and INT conditions compared to the NORM, but there were no differences between EXT and INT conditions. The decreases in KAM and LMF in the EXT condition were expected and concur with past research in other activities. The reductions in the INT condition were unexpected and contradict the literature. This may indicate that participants are making mechanical compensations at other joints to reduce the KAM and LMF in this abnormal internal foot rotation condition.

Key words: Osteoarthritis, cartilage, biomechanics, gait.

Introduction

Ten to 20% of Americans run for recreational purposes regularly (Fields et al., 2010). Many take up running for the health benefits, but the high incidence of injuries makes it difficult for many to continue running regularly. Approximately 50% of Americans who run will experience running related injuries at some point, with 25% of them being injured at any given time (Fields et al., 2010).

The knee joint is the most common site for a running related injury (Taunton et al., 2003), and knee pathologies can increase the chances of developing a degenerative osteoarthritis (OA) in the future (Englund, 2010). OA generally develops in older adults with 10% of people over 55 experiencing symptomatic knee OA, while there are signs of knee OA in 70% of people over the age of 65 (Ostor and Conaghan, 2010). This high prevalence of knee OA could be due to improper loading (as in uneven distribution or loading which the individual is unaccustomed to) of the knee over many years, leading to excessive cartilage wear (Lynn et al., 2008). It has been theorized that a faster mile pace is one factor that can contribute to the increase the radiologic progression of knee OA (Lane et al., 1998), so regular runners may be at increased risk of developing knee OA if they are loading their joints improperly. Approximately 17% of male runners and 6% of female runners are over the age of 55 (Running USA, 2013); therefore, a good portion of the running community is at risk for developing knee joint OA.

Two biomechanical measures that have been associated with knee OA development are the external knee adduction moment (Miyazaki et al., 2002; Wada et al., 2001) and the lateral-medial (LM) shear force positioned medially to the knee joint center during gait (Astephan and Deluzio, 2005, Lynn et al., 2007). The external knee adduction moment (KAM) is generally created during the stance phase when the ground reaction force (GRF) vector is positioned medial to the knee's axis of rotation in the frontal plane and has been prospectively linked to the development of knee OA (Lynn and Costigan, 2008, Teichtahl et al., 2006). The external KAM directly affects the loading of the medial and lateral compartments of the knee (Wada et al., 2001) and the magnitude of this moment is able to predict the magnitude of cartilage loss (Miyazaki et al., 2002). It has been suggested that when the external KAM increases, the load on the medial aspect of the knee joint increases (Lynn et al., 2008). Also, the external KAM is higher during running than it is in walking (Steif et al., 2008), therefore runners may be at greater risk for progression of OA.

Shear forces have also been shown to be detrimental to cartilage health. In vitro studies have shown that cartilage wears away much more quickly under shear stress, both fluid-induced (Smith et al., 1995) and mechanical-based (Radin et al, 1991), and it is believed that these shear forces can help explain OA development and progression (Lynn et al., 2007). Astephen and Deluzio (2005) concluded that the shear forces contributed to cartilage loss more than the external KAM (Astephen and Deluzio, 2005). Therefore, decreasing the magnitude of the external KAM and shear forces on the knees during running could help runners slow cartilage loss and keep their knees healthy longer. However, it is important to note that not all levels of increased stress are detrimental, and that joints/tissues can adapt to the increased stress. The risks may increase during running if the increased stress levels during running are unevenly distributed or not given proper time for adaptation.

Participants with medial knee OA are known to have higher external KAM than asymptomatic controls during the late stance phase of the gait cycle (Lynn and

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Costigan, 2008; Miyazaki et al., 2002). Those with medial knee OA also tend to externally rotate their foot during gait, and this is thought to be an attempt to unload the diseased compartment of their knee (Wang et al., 1990). Foot rotation can alter the external KAM during late-stance while the foot is fully in contact with the ground (Guo et al., 2007; Teichtahl et al., 2006) which may reduce the load on the knee's medial compartment and be helpful in the prevention and/or management of medial compartment knee OA (Teichtahl et al., 2006). Conversely, internal foot rotation has shown mixed results with respect to the external KAM. It has been shown to increase the external KAM (Lynn et al., 2008) which may help unload the lateral compartment of the knee and could be helpful for those with lateral knee OA but has also been shown to decrease the external KAM during walking (Shull et al., 2013) which could unload the medial compartment as medial compartment knee OA is significantly more prevalent than lateral knee OA by a ratio of approximately 5:1 or higher amongst the Caucasian population based on a 2002 study on a Massachusetts subject pool (Felson et al., 2002). A similar relationship between foot rotation and the lateral-medial shear force on the knee has also been established and the possible resultant connection to medial knee OA. Internal foot rotation has been shown to increase the peak medially-directed shear force while external rotation has been shown to decrease it (Lynn et al., 2008). This aligns the increases and decreases in the external KAM with internal and external foot rotation, respectively. These shear forces have not been extensively studied during running trials. Therefore, it is important to investigate ways to reduce shear forces and the external KAM during running.

Given the high prevalence of knee OA and the importance of the knee joint in running, studies are needed that examine strategies to reduce the biomechanical factors implicated in the development of knee OA: the external KAM and LM shear force at the knee. One such strategy would be altering the foot progression angle; however, this has not previously been examined during running. Therefore the purpose of this current study was to examine the effect of foot rotation during running on the external KAM and shear forces in healthy recreational runners. We hypothesize that there will be reductions in the external KAM and LM shear force during the EXT condition compared to the NORM and either increases or no difference during the INT condition compared to the NORM.

Methods

Twenty participants (22.3 ± 3.9 yrs, 1.77 ± 0.10 m, 68.59 ± 10.36 kg, 13 males, 7 females) volunteered for this study. All participants were between the ages of 18 and 35, no history of lower limb trauma/injuries (Williams and Isom, 2012), running a minimum of 10 miles per week for the last six months, and able to hold a pace of 3.35 $m \cdot s^{-1}$ for 30 minutes (Williams and Isom, 2012). The sample size was selected based on previous studies investigating the KAM changes in relation to changing foot angles (Guo et al., 2007; Lynn et al, 2008). The study involved only one visit. All procedures were reviewed and approved by the University Institutional Review Board and the participants signed an informed consent before data were collected.

Participants body mass, height, age, and average number of miles run per week were recorded. A 5-minute warm-up run was then performed at a self-selected pace on a treadmill. Participants were instructed to practice running trials at a pace of 3.35 $m \cdot s^{-1}$ (Schache et al., 2011; Williams and Isom, 2012) across the 20m runway with force plate at 15m using a self-selected degree of foot rotation (Lynn et al., 2008). Trials were performed in three different conditions: normal foot rotation, internally (INT) rotated, and externally (EXT) rotated. Conditions were completed in a randomized order for all subjects. This was repeated until a consistent speed could be maintained, they could hit the force plate with their desired foot consistently, and they became comfortable with running with their foot in EXT and INT. The NORM condition was the subjects running as they would with no direction or intervention while for the EXT and INT conditions, subjects were given simple instructions to externally/internally rotate their foot at whatever degree they felt comfortable with and allowed them to maintain their speed. Once these criteria were achieved, five trials were recorded for each of the three conditions. Foot rotation was initially manually assessed by visual assessment of the testers and subsequently tested through the motion analysis software to ensure the EXT and INT conditions were different than the NORM values. An exact threshold was not set for an absolute rotation difference as the necessity for a specific rotation value during running is non-existent. A TC Timing System (Brower Timing Systems, Draper, UT, USA) was used to ensure participants maintained the prescribed pace (Schache et al., 2011; Williams and Isom, 2012) by placing the timing gates 6.7 m apart on the runway, before and after the force plate.

Retroreflective markers were attached to the participants for both static and dynamic trials. The markers were attached unilaterally to the participant's dominant leg, which was defined as the leg they would prefer to kick a ball with. Rigid marker clusters were attached to the foot, shank, and thigh on the dominant limb as well as the pelvis. Segmental endpoints were defined through anatomical markers placed on the iliac crests, greater trochanters, medial/lateral femoral epicondyles, medial/lateral malleolus, and the base of the 1st and 5th metatarsal (Lynn and Noffal, 2012). Kinematic and kinetic data were collected with a 9-camera Qualisys Oqus 300 motion capture system (Gothenburg, Sweden) at 240Hz and an AMTI force plate (AMTI, Inc., Watertown, MA, USA) at 1200Hz using the Qualisys Track Manager software.

Visual 3-D software (C-Motion Inc., Rockville, MD, USA) was used for data processing. The raw marker data and force plate data were filtered using a second-order low pass recursive Butterworth filter with an 8Hz and 50Hz cutoff frequency, respectively. Marker kinematic data were used to calculate frontal and sagittal plane knee joint angles (the tibia moving relative to the femur) as well as the foot progression angle in the lab coordinate system for each trial. Limb kinematics, GRFs and

Table 1. Means (±SD) of knee kinematic and kinetic variables in three different running positions.

	EXT	NORM	INT
Foot Progression Angle (°)‡	25.53 (4.91)[a]	11.22 (4.18)[b]	-0.54 (5.21)[c]
KAM (Nm/kg) ‡	1.25 (0.38)[a]	1.33 (0.44)[b]	1.21 (0.45)[a]
LMF (N/kg) ‡	4.06 (1.03)[a]	4.40 (1.14)[b]	4.04 (1.21)[a]
Knee ROM—Frontal (°)‡	6.33 (2.63)[a]	4.62 (1.92)[b]	4.48 (1.98)[b]
Knee ROM—Sagittal (°)	27.53 (4.85)	28.89 (4.68)	27.17 (4.95)
VGRF (x BW) ‡	2.48 (0.20)[a]	2.56 (0.20)[b]	2.57 (0.23)[b]

Different superscript letters ("a" and "b") represent a difference between conditions ($p < 0.05$)
‡ = significant main effect for this variable ($p < 0.05$)

participant body mass were used to calculate frontal plane external moments and lateral-medial shear forces at the knee joint in the tibial coordinate system using the standard inverse dynamics link segment model provided by the Visual3D software (Williams and Isom, 2012). Moment and shear force data were normalized by body weight. Shear forces were calculated using the original analogue signal multiplied by the calibration matrix as provided by Visual3D.

Data were evaluated during the stance phase which was defined as the frame of first contact with the force plate until the last frame before the foot left the plate, with a threshold value of 10 Newtons in the vertical direction used to define contact. To limit filtering errors during processing, kinematic marker data were collected with as many motion frames as possible before and after the stance phase. Data collection began as soon as all tracking markers were within view of the camera system (participants began their run out of view of the camera system) and continued until one frame before markers were no longer in view.

The dependent variables were the peak frontal plane external knee moments (all further discussions of moments will be external moments), peak lateral-medial shear force (LMF), and peak vertical ground reaction force (VGRF) during the stance phase. Frontal and sagittal plane knee ROM was calculated from the maximum to minimum angular value. Frontal and sagittal knee ROMs and VGRFs were measured to potentially help explain the changes in KAM and LMF. Transverse plane kinematic curves were also examined but there was a large variability in the shape of these curves among our subjects, making the selection of discreet variables extremely difficult. This may be due to the known errors associated with calculating transverse plane kinematics (Manal et al., 2003). Values were averaged across all trials for each condition for each participant. Trials were discarded if the participant did not make complete contact within the force plate boundaries, if they appeared to alter their stride in order to hit the plate, or if the desired pace was not achieved. The foot progression angle during the three trials was also calculated in relation to the direction of travel at mid-stance when the foot was in full contact with the ground to ensure differences between different conditions.

Dependent variables were tested using repeated measures (EXT, INT, and NORM conditions) ANOVA, with appropriate critical significance level adjusted using Bonferroni corrections and Tukey's post hoc tests when appropriate ($p < 0.05$). The statistics were calculated using IBM SPSS Statistics 20 (IBM Corporation, Armonk, New York, USA).

Results

Repeated measures ANOVAs revealed significant differences between the NORM and the EXT and INT conditions for the KAM, with no significant difference between and EXT and INT conditions (Table 1). The EXT and INT conditions significantly decreased the average values for the KAM, by 6% (effect size= -0.19) and 9% (effect size= -0.27), respectively (Table 1). All participants had peak knee moments in the frontal plane that were external adduction moments (Figure 1) and a lateral to medially directed shear force. The LMF was significantly different between the NORM and both the EXT and INT, with no differences between the EXT and INT conditions. Both the EXT and INT conditions had reductions in LMF from the NORM values. Reductions were 7.7% (effect size = -0.31) and 8% (effect siz = -0.31), respectively (Table 1). EXT condition VGRF values were significantly lower than the NORM and INT conditions, reducing by over 3%.

There were no differences in sagittal plane knee kinematics (Table 1). However, the knee ROM in the frontal plane showed a significant increase during the EXT compared to the NORM and INT conditions (37% [effect size = 0.74] and 41% [effect size = 0.79], respectively). The INT condition showed no significant difference compared to the NORM condition. There was great variability in the dynamic frontal knee kinematics between participants. The position of the knee in the frontal plane was extremely variable between participants as some participants had kinematic values in the abduction direction, while others had kinematic values in the adduction direction (Figure 2).

Discussion

This study examined the effects of different foot rotation conditions on the KAM and LMF. The KAM was shown-to decrease significantly during the EXT as compared to the NORM condition, which aligned with our hypotheses. This coincides with the past research regarding foot rotation during gait (Lynn et al., 2008; Lynn and Costigan, 2008; Teichtahl et al., 2006), stair climbing (Guo et al., 2007), and golf (Lynn and Noffal, 2010). Lynn et al (2008) and Teichtahl et al (2006) both showed reductions in the KAM when participants externally rotated their feet during walking trials (Lynn et al., 2008; Teichtahl et al.,

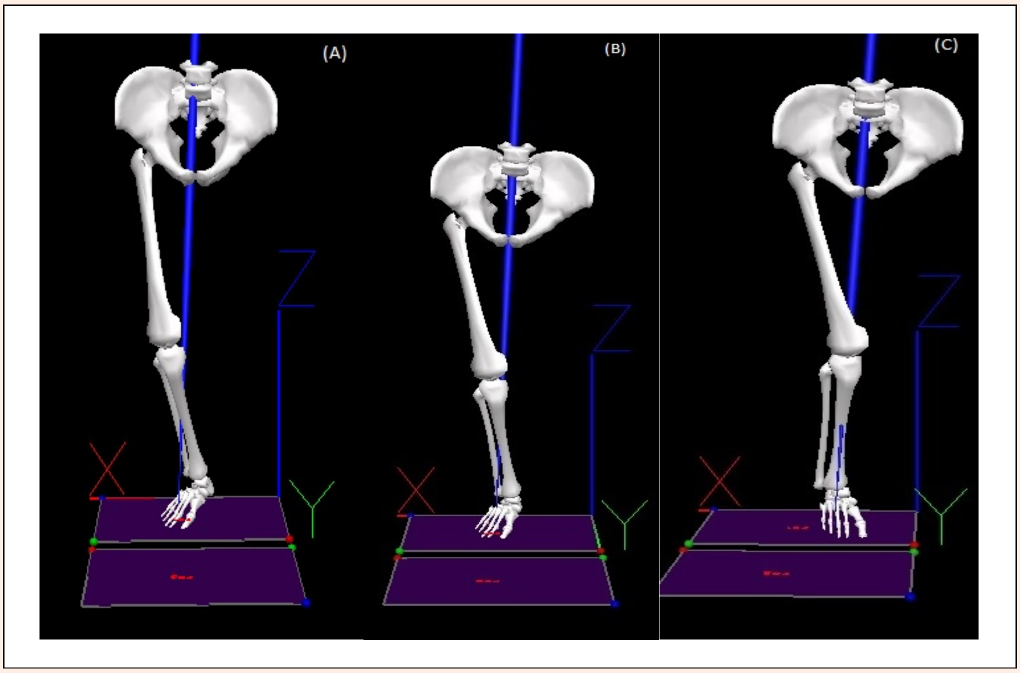

Figure 1. Ground reaction force vectors for runner in EXT condition (A), NORM condition (B), and INT condition (C). The GRF force vectors created an external knee adduction moment in all three conditions for all participants.

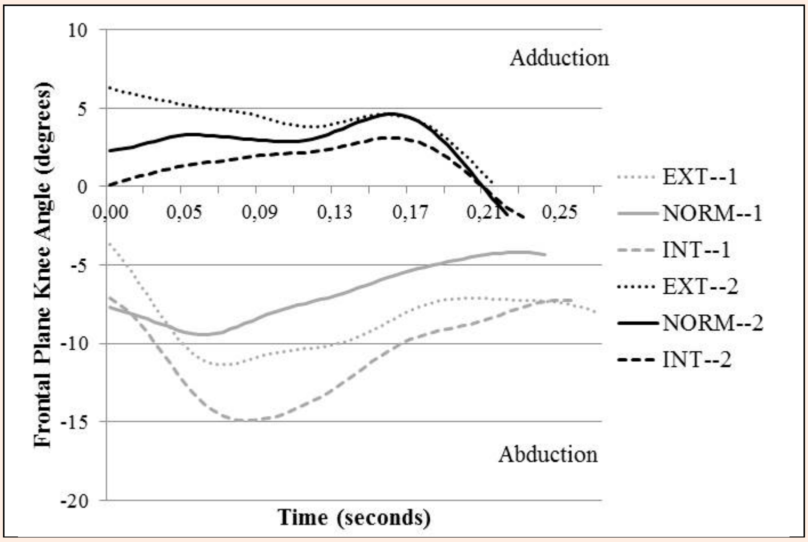

Figure 2. Graph depicting representative trials of frontal plane knee angles for two different participants in all three conditions, illustrating variability between participants. Note: subject 1 was in abduction during all trials while subject 2 was in adduction during all trials.

2006). It has been suggested that utilizing this external rotation intervention may decrease the moment values and shift some of the knee loading onto the lateral compartment, which may help slow the medial knee OA progression (Lynn et al., 2008; Teichtahl et al., 2006); however, Jenkyn et al. (2008) suggested that this may shift load to the sagittal plane knee moments. Although we found a similar trend with respect to the interventions, there were differences between our running KAM values and the walking moments in the literature. First, the magnitude of the peak KAM is much higher in this current work, which was expected given the increased speed of the movement. Second, there was an absence of a double peak in these running KAM as was seen in past research (Figure 3; Lynn et al., 2008; Lynn and Costigan, 2008). Only 4 of our 20 participants had a double peak in their KAM curve, leading to the use of a single peak KAM value. Research has shown that running does not show a double-peak in force values (Damavandi et al., 2012) while walking does. Future research may benefit from examining the differing mechanics leading to a double versus single peak profile.

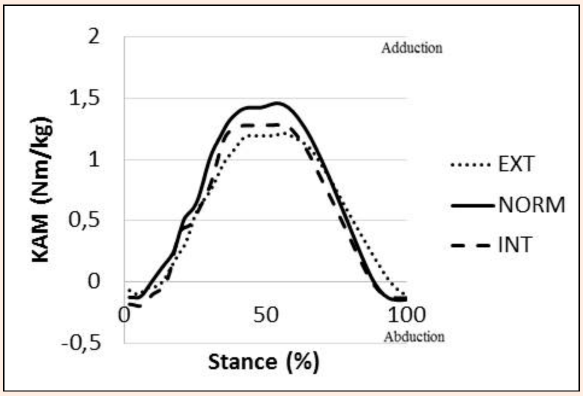

Figure 3. Knee Adduction Moment (KAM) curve for one subject. Four of twenty subjects exhibited a double peak profile, leading to the selection of a single maximum peak value for comparison. All peak frontal plane knee moments were adduction moments.

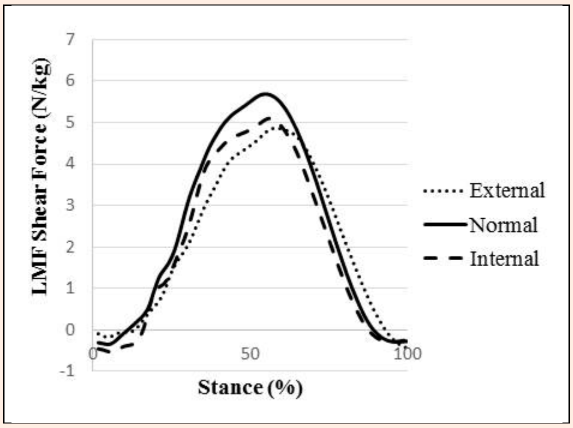

Figure 4. Lateral-medial shear force (LMF) for one subject. As with KAM, a single peak was selected as only four of twenty subjects exhibited a double peak profile. All peak shear forces were medially directed.

Research examining two other movements (golf and stair climbing) has also shown that external foot rotation reduces the KAM. The target side limb during a golf swing had a decreased KAM with EXT rotation (Lynn and Noffal, 2010); while during stair ascent, there was a reduction in the second peak KAM with EXT rotation (Guo et al., 2007). All three motions (walking, stair climbing, and golf) have direct application to this research in that they all displayed reductions in the KAM during an EXT condition; however, it is important to note that the magnitudes of the moments were much higher during running than the other movements. Running showed average values of 1.33 $Nm \cdot kg^{-1}$ and 1.25 $Nm \cdot kg^{-1}$ in the NORM and EXT conditions while the largest KAM measured during gait, stair climbing, and golf was 0.63 $Nm \cdot kg^{-1}$ (Guo et al., 2007; Lynn et al., 2008; Lynn and Noffal, 2010). This supports research indicating that speed of the movement has a direct relationship to the magnitude of moments (Mundermann et al., 2004). Although golf does have some faster segment velocities than running, it is primarily a transverse plane (rotational movement) that still showed the same result using foot external rotation. The larger KAM magnitude in running may make it increasingly more important to find ways to decrease this moment in runners. Therefore, the decreased KAM values during the EXT condition in running may serve as an intervention that could slow the progression of medial OA in runners.

During the EXT condition the LMF displayed similar results to the KAM, showing a 7.7% reduction in average peak values. This is consistent with research examining EXT during walking. As with KAM, LMF didn't show a double peak consistently across participants (Figure 4; only 4 of our 20 participants displayed a double peak) and average peak magnitudes of LMF were increased by approximately 300% over those reported by Lynn et al during walking (Lynn et al., 2008). Shear forces are also known to be more detrimental to cartilage health than pure compressive loading (Smith et al., 1995), adding to the importance of reducing these values in an attempt to slow the progression of knee OA in runners. Both the reductions in the KAM and LMF point to externally rotating the foot during running as a possible intervention to both slow the rate of cartilage loss and/or alleviate the pain in the medial compartment of the knee. Additionally, the VGRF values were also reduced during the EXT condition which has also been shown to help in reducing injury rates (Williams et al., 2000). VGRF values have been hypothesized to be linked to overuse injuries (Cronin et al., 2008), implying that a reduction is beneficial for reducing the overuse injury rate.

While the EXT condition produced the expected results, the INT condition did not conform to our hypotheses. Both the KAM and LMF decreased their magnitudes during INT as compared to the NORM. This reduction is inconsistent with research in several other activities (Lynn et al., 2008; Lynn and Costigan, 2008) as research has shown increases in the KAM and LMF during an INT condition compared to a NORM condition (Lynn et al., 2008) or no statistical difference between the INT condition and NORM condition (Lynn et al., 2008; Lynn and Costigan, 2008). It has been suggested that INT may shift the GRF medially with respect to the knee joint axis of rotation in the frontal plane; therefore increasing the KAM and LMF. Since the KAM and LMF decreased in the INT condition in this current work, participants must have been making compensations in their running movement patterns to avoid placing this large moment on their knees. One other study has shown a decrease in the KAM with INT rotation of the foot during walking due to a medial shift of the knee joint center and lateral center of pressure shift (Shull et al., 2013). It is important to point out that the healthy runners in this study generally exhibit external foot rotation during their normal running gait, as is evidence by the 11° of external rotation during the NORM condition. This suggests a mechanical inclination of these runners to externally rotate their foot and hence, internally rotating the foot would be an extremely unnatural and uncomfortable condition, potentially leading to further compensations in their movement patterns. Trunk lean towards the stance limb has been shown to reduce the KAM (Gerbrands et al., 2014); therefore, perhaps our participants were compensating for the INT condition by leaning their trunk. This is just one possible explanation as trunk position was not measured during this work; however, is it a possible explanation for the reduction in the KAM during the INT condition. Shifts in the center of pressure and moment arms may be created as a result of this possible compensation, which could be further examined in future research.

This research contributes to the idea that EXT will decrease the KAM and LMF which has been hypothesized by previous research to help unload the medial compartment of the knee and slow the progression of medial knee OA, although as compartment loading was not measured, further in vivo research is needed to support this hypothesis. The INT warrants further study given the conflicting literature regarding its effect on knee loading. There are several other future considerations to take into account with this research. First, the EXT and INT conditions should be examined in participants who have medial knee OA. Medial knee OA is more likely to occur in older runners and older runners have been shown to have higher KAM magnitudes than their younger counterparts (Lilley et al., 2013). Participants with OA have also been shown to have higher moments than participants without OA during gait (Lynn and Costigan, 2008). Since the participants in this study were younger and healthy, the intervention should be tested in an older adult population as well. Second, allowing runners to run at their normal self-selected pace may be important as not all runners run at the fixed pace we chose for our study.

Future studies should examine having the participants run at a speed that is determined to be a percentage of the participants' maximum mile speed as different running speeds have been shown to alter kinematics and kinetics in runners (Schache et al., 2011). This could also influence the kinematics and kinetics of the knee. If a runner is only able to run a top speed of 3.5 $m{\cdot}s^{-1}$, they would have been very near their maximal running speed during testing, which would be a much different task compared to a runner with a top speed of 5.0m/s. Static knee alignment may play a role in the outcome of the above studied variables. While it was not measured for this project, it may provide additional insight into the changes seen here. While only discreet points were pulled off of the KAM and LMF curves, it may be beneficial for future research to perform a principal component analysis in order to further examine the time-series curves of the variables of interest, as well as incorporating other possible explanatory variables such as center of pressure or GRF lever arms. Center of pressure differences were not examined, however use of an in-shoe pressure sensor system could be used to help determine if the change in the joint moments is affected by center of pressure changes. Additionally, the data presented here are representative of an acute intervention in foot rotation. It would be beneficial to examine the prolonged effects of foot rotation on the variables of interest in order to examine long term effects as that is important for the OA population.

Conclusion

Utilization of EXT intervention during running may help slow the progression of medial knee OA as it has been shown to unload the medial compartment of the knee by decreasing the KAM and LMF. The INT intervention may have been a much less natural movement as our subjects normal running gait was with their foot externally rotated. This may help explain why this intervention also decreased these variables, which conflicts with some previous research.

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Key points

- External rotation of the foot during running reduced the loads on the medial compartment of the knee
- Internal rotation of the foot also reduced the medial loads, but is a more unnatural intervention
- External and internal rotation reduced the shear forces on the knee, which may help slow the degeneration of knee joint cartilage

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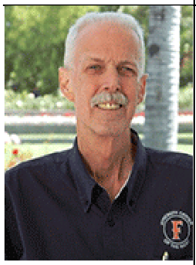

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