Original Article

Ankle and foot mechanics in individuals with chronic ankle instability during shod walking and barefoot walking: A cross-sectional study

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ABSTRACT

Purpose: This study evaluated the angular kinematic and moment of the ankle and foot during shod walking and barefoot walking in individuals with unilateral chronic ankle instability (CAI).
Methods: Recreational soccer players with unilateral CAI were recruited for this cross sectional study conducted between January and August 2019. A total of 40 participants were screened for eligibility but only 31 met the inclusion criteria based on the methods of Delahunt et al and Gribble et al. Except for 3 participants not attending the evaluation session, 28 participants were finally included. A three dimensional motion analysis system made up of ProReflex motion capture unit and an AMTIb Kistler force plate, embedded in the middle of nine meter walkway, were used to assess the ankle and foot angles and moment during shod walking and barefoot walking conditions. A Statistical Package for Social Sciences (version 20.0) was used to analyze data.
Results: During shod walking, the ankle joint plantar-flexion range of motion (ROM) at 10% of the gait cycle (GC) and dorsiflexion ROM at 30% of the GC were significantly higher than those during barefoot walking for both feet ($p = 0.001, 0.001, 0.027$, and 0.036 respectively). The inversion ROM during shod walking was significantly higher than that during barefoot walking for both feet at 10% and 30% of the GC ($p = 0.001. 0.001, 0.001$, and 0.042 respectively). At 10% of the GC, the eversion moment was significantly higher between barefoot and shod walking for both feet (both $p = 0.001$). At 30% of the GC, there was no significant difference between shod and barefoot walking plantar-flexion moment of both feet ($p = 0.975$ and 0.763 respectively), and the eversion moment of both feet ($p = 0.116$ and 0.101 respectively).
Conclusion: At the early stance, shod walking increases the ankle plantar-flexion and foot inversion ROM, and decreases the eversion moment for both feet in subjects with unilateral CAI. Therefore, the foot wearing condition should be considered during evaluation of ankle and foot kinematics and kinetics.
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Introduction

There is a reduction in walking speed, step length, stride length, and double support time during barefoot walking,[1] as well as increased step frequency and single support times, compared to shod walking.[2] These difference are attributed to the higher loading rate during barefoot walking compared to shod walking.[3] The reduced stride length minimizes the discomfort at heel strike during walking with uncushioned shoe.[4] While, shod walking was associated with increased knee varus and hip flexion and extension moments which were closely related to the increased stride length.[5]

The lower limb biomechanics may be affected by the footwear through several mechanisms: the shoes decrease the ankle range of motion (ROM) which may partially prevent the foot rolling process that could change the foot and ankle rocking action which is needed for normal biomechanics of lower extremities.[6] Moreover, the reduction in ROM leads to the loss of the ankle's eccentric control through the period extended from heel strike to flat foot phase that can alter the shock absorption mechanism.[7]

The longitudinal plantar arch appears to be higher during barefoot walking, which may lead to more accommodated load distribution.[8] This higher plantar arch changes the plantar archi-tecture which creates good shock absorption. During contact with the ground, adequate sensory information from the plantar surface

of the foot is an essential component for foot adaptations, which change when wearing shoes.[8,9] During shod walking, the ability of the plantar arch to alleviate load is lost[9] due to the changes in sensory information and the lack of flexibility caused by the shoes, which can be related to the high injury frequency in shod walking conditions.[8,9]

The most frequently injured joints in the lower extremity in conventional running shoes were the knee and ankle joints.[10] Chronic ankle instability (CAI) was mainly caused by lateral ankle sprain which develops to CAI in 30%–40% of patients despite sufficient initial treatment.[11] It is fundamentally known as a continuous complaints of giving way, pain and repeated ankle sprains for at least one year.[12] The CAI is characterized by an increased ankle plantar-flexion, inverted rearfoot, and increased vertical forces on the foot lateral border and exaggerated peroneus longus activity during walking.[13] During barefoot walking there was a decreased ankle dorsiflexion during loading response and a more inverted calcaneus.[14]

During shod walking, the ankle of subjects with CAI were more inverted throughout the gait cycle (GC) and the subtalar joint motions were controlled by invertors moment compared to evertors moment in healthy subjects. In addition to increased ankle joint plantar flexion, there are ipsilateral hip joint adduction and lateral trunk lean towards the affected side.[15] Moreover, the CAI decreased the concentric strength of the plantar-flexors and evertors compared to the contralateral uninjured ankle,[16] and disturbed the normal ankle eccentric strength that may be responsible for the recurrent lateral ankle ligament sprain.[17]

The review study of Moisan et al.[13] has reported that many studies examined the effect of CAI on kinematics, kinetics and muscular activities during shod walking[18,19] and barefoot walking.[20,21] However, there was no research that examined the effect of foot condition (shod or barefoot) on ankle and foot kinematic and kinetic of individuals with CAI. So, this study evaluated the ankle and foot angular kinematics and joints moment during shod and barefoot walking in individuals with CAI. This study hypothesized that subjects with CAI would display similar angular kinematics and moment of the ankle and foot during shod and barefoot walking.

Methods

Subjects

Twenty eight male recreational soccer players with CAI participated in this cross-sectional study, age (25.32 ± 2.78) years; height (176.88 ± 2.98) cm; weight (71.76 ± 3.70) kg. It was conducted between January and August 2019. A total of 40 participants were screened for eligibility but only 31 met the inclusion criteria and were enrolled in the study. Three participants did not attend the evaluation session (Fig. 1). They were referred from orthopedic specialists with a diagnosis of unilateral right CAI, as a first grade ankle instability. They participated voluntary according to the inclusion criteria of Delahunt et al.[22] and Gribble et al.,[23] i.e. (1) at least one significant right lateral ankle sprain in which the subject was unable to walk independently without the aid of crutches (the first sprain took place more than 12 months ago); (2) repeated attacks of lateral ankle injury (the most recent injury must have occurred more than 3 months before participating in the study); (3) feeling of ankle instability, that is called "giving way"; and (4) pain during intense loading and less functional since injury. Moreover, the participants must not be included in a rehabilitation program for CAI.

The sample size calculation was conducted using G*Power 3.0.10 software, with a one tailed comparison of difference between two dependent means. The sample size was determined as 28 participants according to $\alpha = 0.05$, power $= 0.90$ and effect size $= 0.50$.

The exclusion criteria included the following: (1) a previous trauma or surgery to the trunk or lower extremities; and (2) neurological or vestibular impairments with remaining deficits and regular contribution in physical activities training, especially
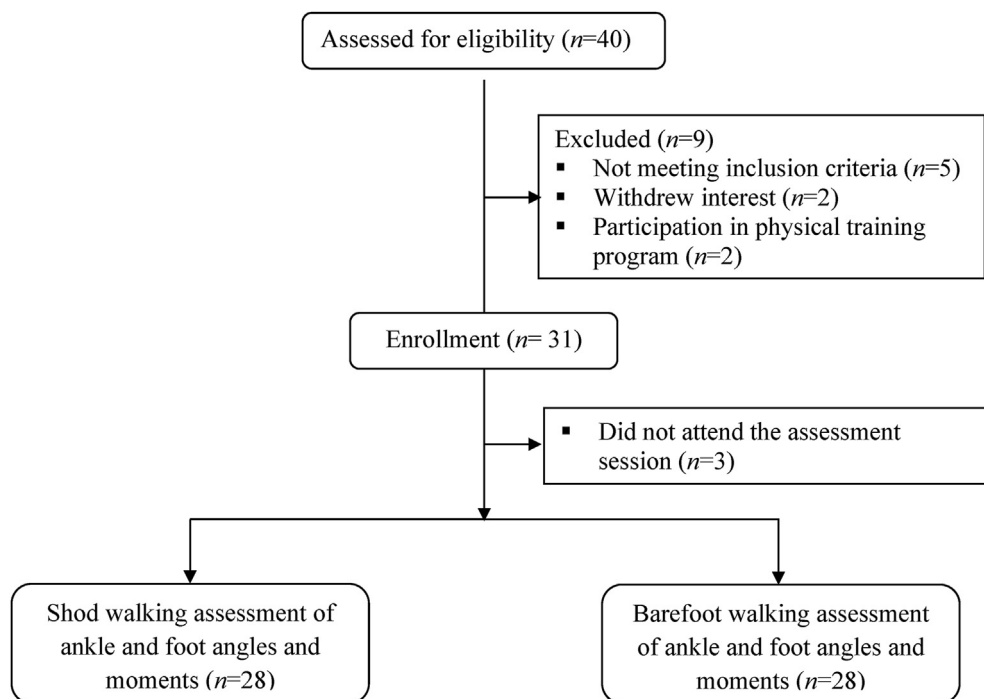

Fig. 1. The participants' flowchart.

cutting maneuvers (more than once a week). This exclusion criterion was added to eliminate the acquired stability effect that might be achieved from activities that train the ankle muscle group.[24] A written consent form was signed by each participant. The study was approved by the local institutional review board of Faculty of Physical Therapy (P.T. REC/012/002040), Cairo University, and conducted in accordance with the Declaration of Helsinki.

Procedure

A three dimensional motion analysis system (Qualisys Medical AB, Gothenburg, Sweden) made up of ProReflex motion capture unit, and an AMTIb Kistler force plate, embedded in the middle of 9 m walkway, was used to collect data. The system had six cameras with a capture capability of 120 frames/seconds (type170120, 100–240 V, 50–60 HZ, 20 W, 230 MA).

As indicated by the user manual/system software, 16 reflective markers were set on twenty bony landmarks: 2 markers set on the two anterior superior iliac spines, 2 markers on the two greater trochanters, 2 markers on the superior surfaces of the two patellae, 2 markers on the lateral surfaces of both knees along the lateral joint lines, 2 markers on the tuberosities of both tibias, 2 markers on the two lateral malleoli, 2 markers on the dorsum of both feet between the bases of the 2nd and 3rd metatarsal bones, and 2 markers on both heels (posterior aspects of calcaneus) at the same horizontal plane level as the toe marker (Fig. 2).

Each participant conducted three walking trials to be familiar with the study procedure before starting the actual measurement. The subjects were assessed at two walking conditions, with shoes (shod) and without shoes (barefoot), while the order of the walking conditions was randomized. After that, the participants were instructed to walk through the walkway at their comfortable walking speed, which was chosen to reduce variations in gait trials. As it has been reported that variability increases when subjects walk faster or slower than their free comfortable walking speed.[25]

Three walking trials were recorded for each participant with fully landed foot on the force plate. The accurate walking trial was used for data processing. According to Dames and Smith,[2] the participants performed the shod walking test condition by using their own athletic shoe with mean shoe mass of (291.08 ± 52.61) g. Bishop et al.[26] reported that markers fixed to the outer surface of the shoe are similar to markers placed to the skin. So, the last 4 markers were placed on the corresponding places in the shoe. The participants had a 5 min resting period between the two testing conditions.

According to Monaghan et al.[27] the required kinematic and kinetic parameters of the right and left ankle and foot in the sagittal and frontal planes were collected at 10% and 30% of the GC. Moreover, this time interval of the GC has been identified as weight acceptance period that starts at heel strike till the end of terminal stance, during which there is the maximum joint displacement of the ankle and foot in all motion planes.[28]

Statistical analysis

A Statistical Package for Social Sciences (Armonk, NY: IBM Corp.) version 20.0 was used to analyze the data. The data were found to be normally distributed as indicated by histograms with normal curves. Moreover, it was confirmed by the non-significant findings of the Shapiro-Wilks normality test ($p > 0.05$). So, the parametric analysis was conducted. A two way analysis of variance was used to investigate the bilateral ankle and foot angular kinematic and joint moment during shod and barefoot walking due to unilateral CAI. The statistical significance was set with probability level ($p < 0.05$).

Results

In general, there was a significant difference in between-subjects effect (walking conditions; $F = 97.68$, $p = 0.00$), and a significant difference in within-subjects effect (body side; $F = 13.47$, $p = 0.001$), and interaction effect (body side* walking conditions; $F = 2.23$, $p = 0.001$). Subsequently, multiple pairwise comparison tests were conducted to identify the source of significance regarding group interactions (barefoot versus shod walking) and body side (right versus left side) factors.

Ankle and foot motions

There was no significant difference between the right (affected) and left foot plantar-flexion through barefoot and shod walking ($p = 0.061$ and 0.738 respectively) at 10% of GC. Moreover, there was no significant difference between the right (affected) and left foot dorsiflexion through both walking conditions at 30% of GC ($p = 0.432$ and 0.363 respectively). During shod walking the ankle joint plantar-flexion ROM at 10% of GC and dorsiflexion ROM at 30% GC were significantly higher than barefoot walking for both feet ($p = 0.001$, 0.001, 0.027 and 0.036 respectively).
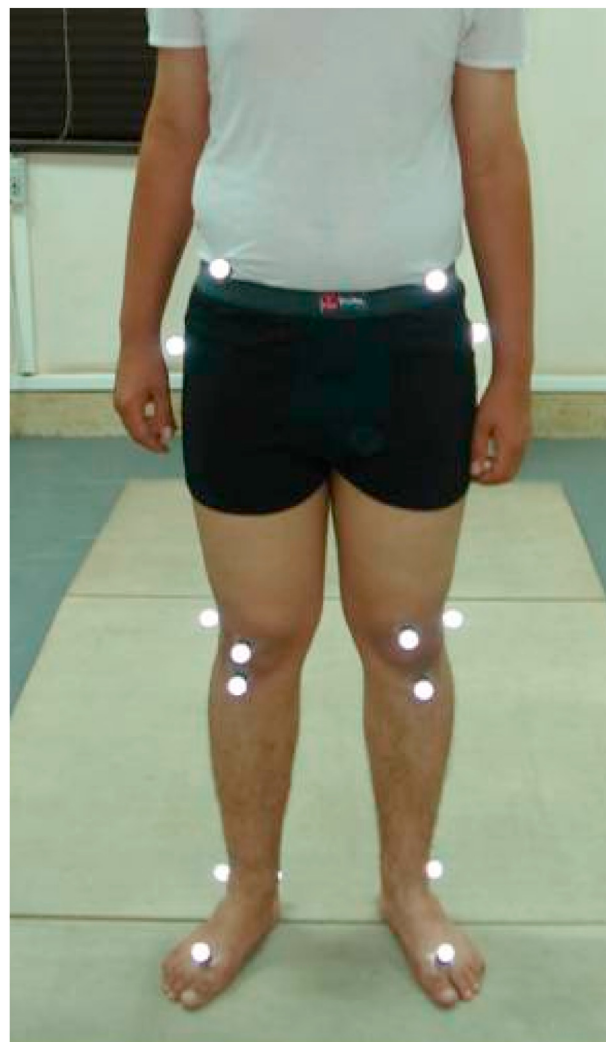

Fig. 2. Set-up of reflective markers.

As for the inversion ROM, there was no significant difference between the right and left foot through barefoot and shod walking at both 10% and 30% of GC ($p = 0.096$, 0.137, 0.155 and 0.517 respectively). During shod walking the inversion ROM was significantly higher than that while barefoot walking for both feet ($p = 0.001$. 0.001, 0.001 and 0.042 respectively), as shown in Table 1.

Ankle and foot moments

There was no significant difference between the right (affected) and left plantar-flexion moment through both walking conditions at 10% of GC ($p = 0.783$ and 0.487 respectively). During barefoot walking there was a plantar-flexion moment and dorsi-flexion moment during shod walking ($p = 0.001$). At 30% of GC, there was no significant difference between the right and left ankle plantar-flexion moment during both walking conditions ($p = 0.890$ and 0.517 respectively). Furthermore, there was no significant difference between shod and barefoot walking plantar-flexion moment at both ankles ($p = 0.984$ and 0.420 respectively), as shown in Table 2.

There was a significant difference between the right and left foot eversion moment during both walking conditions at 10% of GC ($p = 0.023$ and 0.011 respectively). During barefoot walking the subtalar joint eversion moment was significantly higher than shod walking for both feet ($p = 0.001$). At 30% of GC, there was no significant difference between the right and left foot eversion moment during both walking conditions ($p = 0.523$ and 0.567 respectively). In addition, there was no significant difference between shod and barefoot walking eversion moment on both feet ($p = 0.116$ and 0.101 respectively).

Discussion

It was observed that there was no difference between the right and left foot angular kinematics during shod and barefoot walking conditions that was consistent with Sousa et al.[29] who concluded that the individuals with unilateral CAI had an increased proprioception error in the injured and uninjured limbs. Furthermore, the bilateral inverted foot position in the weight acceptance period of the GC agreed with Monaghan et al.[27] who found more inverted foot during heel strike till mid-stance. The inverted foot position may be attributed to the defect in the position sense of ankle joint in subjects with a history of recurrent ankle sprains.[30]

The increased ankle plantar-flexion and subtalar inversion ROM during shod walking were higher than barefoot walking, contrary to Campbell et al.[31] who found that the peak plantar-flexion occurred at the end of stance phase during barefoot walking compared to shod walking. Additionally, during early stance of barefoot walking, there is an eversion peak, whereas during shod walking there is an inversion peak, which occurred more early compared to the eversion peak in barefoot walking. This discrepancy could be refereed to their participants were free from any musculoskeletal injuries.

The studies that compare the three dimensional motion between shod and barefoot walking are limited.[31] Drewes et al.[32] found that the CAI group had small dorsiflexion ROM compared to healthy subjects from 9% to 25% of the GC during barefoot jogging. This is inconsistent with the current findings, which displayed an increased ankle dorsiflexion at 30% of the GC during barefoot and shod walking. Moreover, this movement during shod walking was greater than barefoot walking for both feet.

Furthermore, during shod walking the ankle and subtalar joint ROMs were higher than those during barefoot walking for both feet, which does not concur with the findings of van Schie.[6] This

Table 1
Ankle and foot sagittal (plantar-flexion/dorsiflexion) and frontal (inversion/eversion) range of motions (degree) during barefoot and shod walking.

| Ankle and foot | Sagittal plane (plantar-flexion/dorsiflexion) | | | | | | | | Frontal plane (inversion/eversion) | | | | | | | |
| | 10% Gait cycle | | | | 30% Gait cycle | | | | 10% Gait cycle | | | | 30% Gait cycle | | | |
	Barefoot	Shod	F value	p value	Barefoot	Shod	F value	p value	Barefoot	Shod	F value	p value	Barefoot	Shod	F value	p value
Right (Affected)	5.92 ± 1.25	11.96 ± 0.82	407.03	0.001	−12.31 ± 2.66	13.87 ± 2.93	3.87	0.027	2.80 ± 0.46	4.09 ± 0.22	170.17	0.001	0.68 ± 0.11	1.02 ± 0.18	65.19	0.001
Left	6.51 ± 1.51	11.86 ± 0.55	277.68	0.001	−11.76 ± 3.00	13.23 ± 3.04	2.95	0.036	2.66 ± 0.47	3.97 ± 0.26	149.23	0.001	0.79 ± 0.28	0.96 ± 0.11	7.82	0.042
F value	19.67	0.62			10.63	14.28			12.90	10.35			6.60	1.36		
p value	0.365	0.881			0.432	0.363			0.096	0.137			0.155	0.517		

Data are presented as mean ± standard deviation; p value < 0.05 means significant difference; the negative (−) sign indicates dorsiflexion.

Table 2
Ankle and foot sagittal (plantar-flexion/dorsiflexion) and frontal (inversion/eversion) moments (N.m/kg) during barefoot and shod walking.

Ankle and foot	Sagittal plane (plantar-flexion/dorsiflexion)								Frontal plane (inversion/eversion)							
	10% Gait cycle				30% Gait cycle				10% Gait cycle				30% Gait cycle			
	Barefoot	Shod	F value	p value	Barefoot	Shod	F value	p value	Barefoot	Shod	F value	p value	Barefoot	Shod	F value	p value
Right (Affected)	0.61 ± 0.15	0.15 ± 0.04	215.72	0.001	1.31 ± 0.29	1.31 ± 0.27	0.01	0.984	0.40 ± 0.03	0.32 ± 0.04	53.93	0.001	0.23 ± 0.04	0.21 ± 0.04	2.50	0.116
Left	0.60 ± 0.17	0.17 ± 0.04	149.07	0.001	1.30 ± 0.26	1.36 ± 0.28	0.67	0.420	0.37 ± 0.04	0.29 ± 0.04	48.71	0.001	0.24 ± 0.04	0.22 ± 0.04	2.76	0.101
F value	0.12	0.72			0.09	1.91			22.32	28.06			1.80	1.44		
p value	0.061	0.738			0.890	0.517			0.023	0.011			0.523	0.567		

Data are presented as mean ± standard deviation; p value < 0.05 means significant difference.

may be attributed to the participants of the current study suffering from CAI. Subjects with CAI exhibited a more inverted foot position before, at, and immediately after heel strike during barefoot walking compared to controls.[20] Also, Drewes et al.[32] showed that during barefoot walking, the CAI group demonstrated more rearfoot inversion that was coincident with the findings of the present study. However, this finding disagreed with the results of De Ridder et al.[33] who found a greater eversion angle in CAI group compared to controls from 11% to 73% of the stance phase.

During the two walking conditions there was a significant attenuation in the dorsiflexion moment that leads to a decreased control of the foot during descending to the ground, especially in early stance phase, which increased the probability of recurrent ankle sprain, particularly during shod walking. This can be explained by the additional moment of the shoes weight, and the longer lever arm caused by the heel of the shoe.[34] Touching down the ground with plantar-flexed foot could be the mechanism responsible for recurrent ankle sprain in subjects with previous episodes of ankle injuries. Meanwhile, the subtalar angle during touching the ground does not have considerable influence on ankle sprain.[35]

The result of the present study disagreed with Kung et al.[28] who reported that during shod walking there is a greater maximal dorsiflexion moment. However, barefoot walking created a higher subtalar inversion moment. The participants' age, health, and the assessment method may be the cause of this contradiction. In their study, a treadmill walking using standardized shoes was utilized compared to over-ground walking while wearing the personal athletic shoes in the current study. The different shoes models may provide a different support amounts, cushioning, and sole stiffness. These differences in shoe structure may have confusing effects on the subtalar motion, and kinetics particularly during weight acceptance and propulsion periods.

The ground reaction force usually everts and dorsiflexes the ankle joint as it works laterally to the subtalar joint and anterior to the ankle joint, which is counteracted by strong plantar-flexors and invertors. The joint axis moves medially when the foot is everted, and laterally when the foot is inverted.[36] The inverted weight bearing ankle is likely to create an external load, which drives the foot into inversion. This typically occurs in subjects with CAI. During barefoot walking, the line of action of the ground reaction force is little far from the subtalar joint axis. So, the ankle normally precludes the external inverting torque.[37] The compensatory mechanism tried by CAI subjects is the lateral shift of the centre of pressure (COP), which leads to a greater force under the lateral foot during stance phase.[38] The purpose of this lateral shift of COP is to restore the altered relation between COP path and subtalar joint axis, which may explain the eversion moment during shod and barefoot walking.

During shod walking, the COP is laterally deviated from 25% to 90% of the stance phase.[18] Recently, Koldenhoven et al.[19] found that the COP laterally deviated throughout the stance phase, and increased the peak pressure and pressure-time of the lateral forefoot, which led to deviations in gait mechanics, resulting in subsequent ankle sprains. These findings are another explanation of the eversion moment of the rearfoot during shod and barefoot walking.

During the weight acceptance period, the foot is controlled by evertors concentric moment in CAI group compared to invertors eccentric moment in healthy subjects.[27] This mechanism supports the current findings. During shod walking, the tibialis anterior was more active in CAI group from 15% to 30% and 45%−70% of the stance phase. The peroneus longus activation was greater in CAI group at initial heel strike and toe off and moved lower from 20% to 40% of the stance phase compared to healthy group.[18] Moreover, the CAI group has an increase in the peroneus longus, and medial gastrocnemius activities during 100 ms pre-initial contact.[19] These findings are coincident with the present results. Meanwhile, there was a decrease in the concentric inversion strength, without difference in evertor muscles strength, inversion joint position sense or peroneal latency in response to a perturbation.[39] These results support the predominant eversion moment during barefoot and shod walking at the weight acceptance period of the GC, this evertor moment counteracts the supination moments that causes ankle instability.

There are some limitations with this study. First, all subjects wore their own athletic shoe that was an essential decision to make the test more natural and functional. Second, the sagittal and frontal planes movements of the ankle and foot were assessed without consideration of the hip joint. It is reported that during walking CAI changes the hip-ankle coordination in stance phase.[40] Further studies are needed to explore the relationship between the ankle joint and the more proximal joints during shod and barefoot walking. Third, the changes in kinematics and kinetics during shod and barefoot walking may be accomplished by either changing spatiotemporal parameters, or shifting the location of the forces act upon the foot at heel strike or a combination of both strategies,[28] which should be examined in the future research. Finally, this study was conducted during walking without consideration of running activities. So, it is recommended to conduct further research during running gait.

In conclusion, this study reported differences in the angular kinematic and joints moment of the ankle and foot during shod and barefoot walking in individuals with CAI. Wearing shoes increases the ankle plantar-flexion ROM during early stance phase, the dorsiflexion ROM in the middle of the stance phase, and the inversion ROM of both feet. However, at early stance, there is an increased eversion moment during barefoot walking compared to shod

walking. Therefore, the foot wearing condition should be considered during the evaluation of ankle and foot kinematics, and kinetics in subjects with CAI.

Funding

Ethical statement

The study was approved by the local institutional review board of Faculty of Physical Therapy (P.T. REC/012/002040), Cairo University, and conducted in accordance with the Declaration of Helsinki.

Declaration of competing interest

There are no conflicts of interest that may have influenced this manuscript.

Acknowledgements

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