A prospective study on gait-related intrinsic risk factors for lower leg overuse injuries

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ABSTRACT

Objective: To determine prospectively gait-related risk factors for lower leg overuse injury (LLOI).

Design: A prospective cohort study.

Setting: Male and female recruits from a start-to-run (STR) programme during a 10-week training period.

Participants: 131 healthy subjects (20 men and 111 women), without a history of any lower leg complaint, participated in the study.

Interventions: Before the start of the 10-week STR programme, plantar force measurements during running were performed. During STR, lower leg injuries were diagnosed and registered by a sports physician.

Main Outcome Measures: Plantar force measurements during running were performed using a footscan pressure plate.

Results: During the STR, 27 subjects (five men and 22 women) developed a LLOI. Logistic regression analysis revealed that subjects who developed a LLOI had a significantly more laterally directed force distribution at first metatarsal contact and forefoot flat, a more laterally directed force displacement in the forefoot contact phase, foot flat phase and at heel-off. These subjects also had a delayed change of the centre of force (COF) at forefoot flat, a higher force and loading underneath the lateral border of the foot, and a significantly higher directed force displacement of the COF at forefoot flat.

Conclusions: These findings suggest that a less pronated heel strike and a more laterally directed roll-off can be considered as risk factors for LLOI. Clinically, the results of this study can be considered important in identifying individuals at risk of LLOI.

The number of injuries related to running has increased due to the growing popularity of running. The overall yearly incidence rate for running injuries varies between 37% and 55%.[1] A running injury is defined as an injury or pain on a localised area that requires a change or reduction in training, a visit to a health professional, or the use of medication on a consistent basis.[2 3] Approximately 50–75% of all running injuries appear to be overuse injuries due to constant repetition of the same movement.[1] Running implies repetitive loading of the lower extremity by repeated impact between the foot and the ground. An overuse injury occurs when a structure is exposed to a large number of repetitive microtrauma and forces.[4]

Both intrinsic and extrinsic factors contribute to overuse injuries. Extrinsic factors, which commonly contribute to overload, include poor technique and improper changes in the duration or frequency of activity. Intrinsic factors are biomechanical abnormalities unique to a particular athlete.[5] The biomechanical abnormalities of the lower limb have frequently been described as causative factors for lower limb injuries.[6] There is some progress in the understanding of the biomechanics of the ankle joint complex, especially in the coupling mechanism between foot and leg. However, various mechanisms causing overuse injuries to the lower extremities are still not well understood.[7]

In recreational runners, there is no evidence that static abnormal biomechanical alignment measurements of the lower limb are related to lower limb injuries except in the patellofemoral pain syndrome.[8] Many articles cite pes planus as an important risk factor for overuse injuries, but this assumption is made on theoretical models and cross-sectional studies. To predict injuries, prospective studies need to measure potential risk factors in subjects before the occurrence of an injury.[9] Cross-sectional studies relate potential risk factors with certain injuries, but do not allow clinicians to establish causal relationships. Therefore, in order to identify true gait-related risk factors in runners, there is a need for prospective studies.

To date, to our knowledge, no prospective studies exist examining gait-related risk factors for lower leg overuse injuries (LLOI).[10–12] Therefore, the purpose of this study was to determine prospectively gait-related intrinsic risk factors for LLOI.

MATERIALS AND METHODS

Subjects

To be eligible for this study, the subjects were not to have been familiar with running before the start of this closely supervised 10-week start-to run (STR) programme. Before the start of this running programme, all subjects visited the same physician for a comprehensive injury history. Exclusion criteria were history of a surgical procedure involving the lower limb, or a history of an injury to the lower leg, ankle or foot within 6 months before the start of the study. None of the subjects used prophylactic ankle bracing or taping before and during the study.

One hundred thirty-one healthy subjects (20 men and 111 women) were willing to participate. The subjects were recruited from two STR programmes, organised in April 2006 and April 2007. In all subjects the anthropometrical characteristics and plantar pressures were measured before the STR programme. Some important extrinsic risk factors for overuse injuries (training programme, coach and running surface) could mainly be controlled by selecting subjects from the same athletic club. None of the subjects participated in extramural sports activities during or before the STR programme.

The STR programme consisted of three running sessions per week for 10 weeks. The subjects were followed for the occurrence of injuries throughout the STR programme and were asked to report all resulting injuries to the sports physician who was present at every training session. All sports injuries that occurred during the programme were registered on a standardised form. The aim of this study was explained to each subject and they all signed an informed consent. The study was approved by the ethical committee of the Ghent university hospital.

Plantar pressure measurements

The dynamic force distribution pattern during running at a self-selected pace was examined before the start of the 10-week STR programme using a footscan pressure plate (RsScan International, Olen, Belgium). This device has been proved to reveal deviant gait characteristics in a previous prospective study.[12]

Before the STR programme, all subjects underwent plantar pressure measurements during barefoot running. By running barefoot, discrepancies attributable to footwear were controlled. Barefoot is an accepted baseline state in running analysis.[13] Willems *et al*[11] indicated that gait-related risk factors for exercise-related lower leg pain (ERLLP) are more distinct in the barefoot than the shod condition.

A footscan pressure plate (RsScan International, 2 m × 0.4 m, 16 384 sensors, 480 Hz) was placed right in the middle of a 15-m-long runway. The runway was covered by a thin rubber mat so that the pressure plate would not be visible to the subjects. Following the standard calibration trial, the subjects were asked to run barefoot at a self-chosen, comfortable, moderate velocity along the runway. All subjects were allowed to familiarise themselves with the procedures before data collection. Three valid left and three valid right stance phases were measured. A trial was considered to be valid when the following criteria were met: stance phase registered as a heel strike pattern and no visual adjustments in step length or step frequency to aim on the pressure plate. De Cock *et al*[14] found the temporal plantar pressure variables measured with the footscan plate reliable (intraclass correlation coefficient >0.75).

Data analysis

Eight anatomical zones were identified by the software (Footscan software 7.0 Gait 2nd Generation; RsScan International), controlled and adapted (if necessary) by the researcher.[11] These areas were defined as medial heel (H_M), lateral heel (H_L), metatarsal heads (M_1, M_2, M_3, M_4 and M_5) and the hallux (T_1)[14] (fig 1).

For all those regions, several parameters were calculated: peak force, absolute force–time integrals (mean force × loaded contact time), relative force–time integrals (absolute force–time integrals × 100/sum of all force–time integrals) and temporal data (ie, time to peak force, instants on which the zones make contact and instants on which the zones end foot contact).

Five events were used to divide the stance phase into four time periods.[15] The events were first foot contact (FFC, the instant the foot made first contact with the pressure plate), first metatarsal contact (FMC, the instant one of the metatarsal heads made contact with the pressure plate), forefoot flat (FFF, the first instant when all metatarsal heads touched the plate), heel-off (HO, the instant the heel region lost contact with the plate) and last foot contact (LFC, the last contact of the foot on the plate). Based on these instants, total foot contact could be divided into four phases: initial contact phase (ICP: FFC → FMC), forefoot contact phase (FFCP: FMC → FFF), foot flat phase (FFP: FFF → HO) and forefoot push-off phase (FFPOP: HO → LFC).[14]

Nine mediolateral force ratios were calculated at these five instants of foot contact (table 1) and during the four phases.[16] The X-component (mediolateral) and Y-component (anteroposterior) of the centre of force (COF) scaled to the foot width and foot length were analysed. The positioning and displacement of the components were calculated at the five instants and for the four phases.[16] The mean of all kinetic data was taken from the three trails. De Cock *et al*[14] have shown that the mean of three trials is significantly reproducible for analysis.

Statistical analysis

Before the statistical analysis, the subjects were divided into two groups: a group who developed an injury (injured group) and a group who did not (uninjured group) throughout the 10-week programme. To identify the gait-related intrinsic risk factors for LLOI, binary logistic regression analysis[17] was used to analyse the data. Therefore, all variables were entered separately into the logistic regression. Statistical significance was accepted at the level of $\alpha<0.05$. Odds ratios (OR) and 95% CI were calculated on the indices measuring gait-related risk factors. The indices were standardised before entering into the logistic regression analysis. Then, the OR models have been adjusted for age and sex in gait-related intrinsic risk factors. Statistical analysis was performed with SPSS for Windows version 15.

RESULTS

During the STR training period, 27 subjects (five men and 22 women) developed a LLOI. From these 27 subjects (20.62%), eight developed bilateral complaints. Consequently, the injured group comprised 35 lower limbs. For this group, only the data from the injured leg were used for analysis. The uninjured group consisted of both lower legs of the 104 uninjured subjects. Before the statistical analysis, the data from both legs of the same subject were collapsed into one single measurement by taking the average of those in order to make an adjustment for the correlation between the two legs of the same person.[18]

There were no significant differences between both groups with respect to their sex, average age, height and weight. The anthropometric data of both groups are presented in table 2 ($p>0.05$). No significant differences between the two groups were observed for temporal force data and relative force–time integrals.

Logistic regression analysis showed that in the injured group the force distribution was significantly more laterally directed at first metatarsal contact (mediolateral force ratio 1, 2, 3 and 8) and at forefoot flat (mediolateral ratio 1 and 3). Furthermore, mediolateral force ratio 8 showed more displacement of the force from medial to lateral in the initial contact phase ($p=0.047$, OR 0.62; table 3).

During the forefoot contact phase and the foot flat phase, the mean value of the x-component of the COF was more laterally directed in the injured group and more medially directed in the uninjured group (table 3). A positive value indicates a force medially directed of the heel-M2 axis and a negative value indicates a force laterally directed of the heel-M2 axis. At heel-off the x-component of the COF is situated significantly more

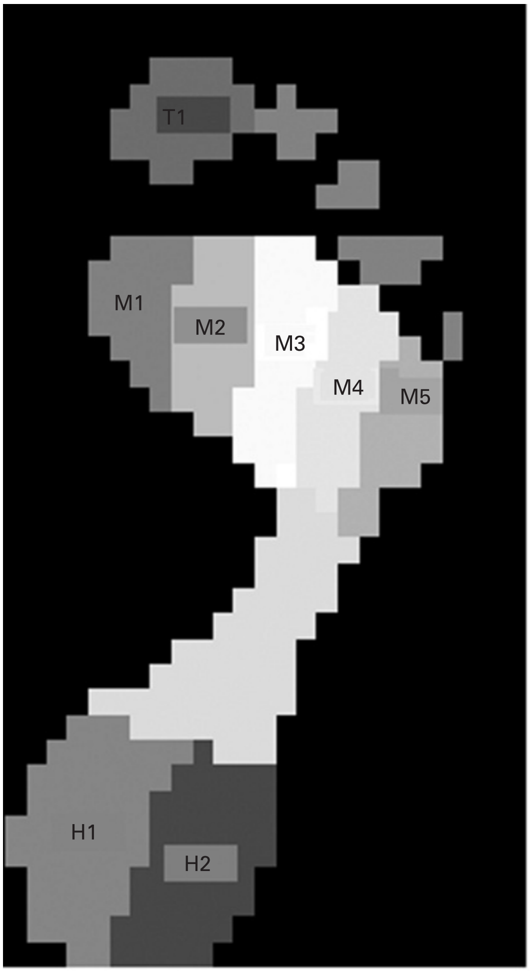

Figure 1 The location of the eight anatomical areas on a foot print (Footscan software 7.0 Gait 2nd Generation, RsScan International). H_L, lateral heel; H_M, medial heel; M_1, M_2, M_3, M_4 and M_5, metatarsal heads; T_1, hallux.

laterally (p = 0.004, OR 0.76). During the forefoot push-off phase the x-component of the COF is situated significantly more medially (p = 0.023, OR 1.64).

Logistic regression analysis revealed that the velocity of the mediolateral (p = 0.027, OR 0.50) and the anteroposterior (p = 0.050, OR 0.65) displacement of the COF at forefoot flat was significantly slower in the injured group. The COF shifted less quickly in those runners who developed LLOI. Also, anteroposterior displacement of the COF at forefoot flat was significantly higher in the injured group (p = 0.015, OR 1.47). The analysis revealed that the peak force and the absolute force–time integral underneath metatarsal five was significantly higher in the subjects who sustained LLOI (table 3). Furthermore, when the OR were adjusted for age and sex the results did not noticeably change (table 3).

DISCUSSION

In overuse injuries of the leg, abnormal foot biomechanics is considered as an important intrinsic risk factor.[7 19] In spite of some significant progress in the understanding of the biomechanics of the ankle joint complex, the relationship between this and the development of overuse injuries is still poorly understood.[7 19] The present investigation is the first study to determine prospectively dynamic biomechanical intrinsic risk factors for LLOI.

Table 1 List of mediolateral force ratios

Ratio 1	[(H1 + M1 + T1) − (H2 + m4 + m5)]/sum(T1 : H2)*
Ratio 2	[(H1 + M1 + M2) − (H2 + m4 + m5)]/sum(T1 : H2)*
Ratio 3	[(H1 + M1) − (H2 + M4 + m5)/sum(T1 : H2)*
Ratio 4	[(M1 + M2) − (M4 + M5)]/sum(M1 : M5)†
Ratio 5	[(M1 + M2) − (M3 + M4 + M5)]/sum(M1 : M5)†
Ratio 6	(M1 − M5)/sum(M1 : M5)†
Ratio 7	(M1 + M2)/(M1 + M2 + M4 + M5)
Ratio 8	(M1 + M2 + H1)/(M4 + M5 + H2)
Ratio 9	[(M1 + M2) − (M4 + M5)]/(M1 + M2 + M4 + M5)

*Sum of forces underneath all areas. †Sum of forces underneath all metatarsal heads.

The results of this study indicate no significant difference between any of the anthropometric characteristics and the occurrence of LLOI. These results are in agreement with some prospective studies that have reported no significant relationship between body size and injuries.[10 20–22]

In this study, logistic regression analysis of plantar pressure measurements during gait revealed some gait-related intrinsic factors as predicting factors for the development of LLOI. These factors are: (1) a more laterally directed force distribution during the initial contact phase at first metatarsal contact and in forefoot flat; (2) a more laterally directed force displacement in the forefoot contact phase, the foot flat phase and at heel-off, a delayed change of the displacement of the COF at forefoot flat and a highly directed anteroposterior force displacement of the COF at forefoot flat; and (3) a higher force and loading underneath the lateral border of the foot. This study found no significant differences between the two groups for temporal force data and relative force–time integrals.

This study revealed that the running pattern of the subjects who developed LLOI differed from that of subjects who remained injury free. Therefore, this study showed that a less medial foot roll-off, with a higher loading underneath the lateral side of the foot, can be considered as a risk factor for LLOI.

The results of the analysis of the mediolateral force ratios showed that in the group who developed LLOI, plantar force distribution was significantly more laterally directed during the initial contact phase (ratio 8) and at first metatarsal contact (ratio 1, 2, 3 and 8) compared with the uninjured group. This could indicate that in the injured group the foot pronates less at the first metatarsal contact of the gait pattern compared with the uninjured group. This finding is in agreement with previous studies in runners who developed anterior knee pain and who showed 25% less pronation during the first 10% of the support phase compared with non-injured runners.[10 23] An adequate pronation of the foot is necessary to have an appropriate shock absorption. Therefore, less pronation may cause a more rigid landing and thereby increase the shock to the lower leg, which contributes to overuse injury. In addition, the smaller shock absorption transfers a larger part of the ground-reaction force to the lower leg. Abnormal pronation may thus result in abnormal internal tibial torsion, affecting stress exerted along the entire lower limb.[24]

The ratios of the present study showed a different distribution of the mediolateral force ratios, with lateral loading almost on the whole foot (ratio 1 FFF and ratio 3 FFF). In addition, in the LLOI group, there was a more laterally directed force distribution during the initial contact phase. One possible explanation could be related to poor proprioception in this group. A mechanism of anticipatory movement is likely to the feedback information of proprioception,[25] as the body's awareness to position and move in space.[26] In gait, if the body is not

Table 2 Mean (SD), crude OR and p value for the age, height, weight and sex of the whole group, the uninjured group and the injured (lower leg overuse injury) group ($\alpha<0.05$)

Characteristics	Mean (SD)	Uninjured group	Injured group	OR	p Value
Age, years	39.09 (10.3)	38.70 (10.72)	40.59 (8.44)	1.20	0.395
Weight, kg	70.33 (11.31)	69.61 (11.00)	73.11 (12.24)	1.35	0.155
Height, cm	168.47 (7.77)	168.43 (7.97)	168.62 (7.10)	1.03	0.906
Gender					
Men (%)		15 (75)	5 (25)	1.35	0.599
Women (%)		89 (80.2)	22 (19.8)		

OR, odds ratio.

aware of the movement or positions of the limb segments, it may not be able to prepare the loading at initial contact effectively.[26]

This study also identified the mediolateral displacement of the COF during forefoot contact phase, foot flat phase, forefoot push-off phase and at heel-off as an intrinsic risk factor for the development of LLOI. During the forefoot contact phase, the foot flat phase and at heel-off the x-component of the COF was more laterally directed to the heel-M2 axis of the foot in the injured group compared with the uninjured group. This indicates that subjects who developed LLOI have a more supinated pattern at the mid and late stance phase of gait. This is probably caused by the increased load at the metatarsophalangeal joint due to delayed displacing of the COF at forefoot flat. This finding is in accordance with the work of Burns *et al*,[27] who revealed that triathletes with supinated feet are more likely to sustain an overuse injury in a 10-week prospective study. However, the x-component of COF was displaced more medially during the forefoot push-off phase in the injured group. This suggests that the roll-off occurs across the hallux. This may indicate a preparation of the foot to provide a rigid lever at the push-off phase. In contrast, Willems *et al*[16] revealed that the mediolateral ratios and the centre of pressure were more laterally displaced in the forefoot push-off phase. They concluded that roll-off does not occur across the hallux. However, the reason for that was not biomechanically clear.

In the group who developed LLOI during this study, a more lateral roll-off appeared according to the increased absolute force–time integral and peak force underneath metatarsal five. In contrast with this study, Hintermann and Nigg[7] reported that an excessive pronation (approximately 2–4° greater than the group with no injury) has been typically associated with the development of overuse injuries in locomotion.

Traditionally, the pronated or pes planus foot type has been cited as a risk factor for injury, but only a few researches have provided prospective evidence for such an association. Willems *et al*[12] recently revealed that subjects who developed ERLLP had a significantly more increased pronation than the control group. They suggested that overpronation was associated with an increased incidence of ERLLP.

After adjusting for sex and age, the OR in this study did not noticeably change. According to these results, for some identified risk factors a high score meant a higher risk of becoming injured (eg, the x-component of COF during forefoot push-off phase (1.67), anteroposterior displacement of the COF at forefoot flat (1.75), absolute force–time integral (1.72) and peak force underneath metatarsal five (1.68)). For some others a lesser score meant a higher risk of becoming injured (table 3). In this study, the mediolateral displacement of the COF during forefoot contact phase was the most important risk factor to develop a LLOI. For this parameter a decrease of 1 SD increased the risk of LLOI 2.5 times.

We could not find a straightforward explanation for the discrepancy between this study and the study by Willems *et al*.[12] However, in our opinion, it seems plausible that when the normal physiological loading of the joint is exceeded by overuse, both deviations of the normal roll-off pattern of the foot,

Table 3 Mean (SD), crude and adjusted OR (95% CI) and p value for total group, the uninjured group and the injured group

	Mean (SD)	Mean (SD) (uninjured group)	Mean (SD) (injured group)	Crude OR (95% CI)†	p Value	Adjusted OR (95% CI)*	p Value
Ratio 1 FMC	−0.015 (0.141)	0.001 (0.111)	−0.001 (0.214)	0.63 (0.42 to 0.95)	0.029	0.63 (0.42 to 0.96)	0.032
Ratio 2 FMC	−0.015 (0.140)	0.001 (0.112)	−0.075 (0.214)	0.64 (0.42 to 0.96)	0.031	0.65 (0.43 to 0.98)	0.038
Ratio 3 FMC	−0.015 (0.141)	0.001 (0.111)	−0.077 (0.214)	0.63 (0.42 to 0.95)	0.029	0.64 (0.42 to 0.97)	0.035
Ratio 8 FMC	1.026 (0.221)	1.053 (0.201)	0.925 (0.268)	0.58 (0.38 to 0.89)	0.013	0.58 (0.38 to 0.90)	0.016
Ratio 1 FFF	−0.031 (0.108)	0.021 (0.106)	−0.070 (0.113)	0.63 (0.41 to 0.98)	0.038	0.65 (0.41 to 1.01)	0.057
Ratio 3 FFF	−0.033 (0.108)	−0.023 (0.105)	−0.073 (0.111)	0.62 (0.40 to 0.96)	0.031	0.63 (0.40 to 0.99)	0.047
Ratio 8 ICP	0.257 (0.190)	0.273 (0.194)	0.192 (0.163)	0.62 (0.39 to 1.00)	0.047	0.59 (0.36 to 0.96)	0.033
x-comp HO	2.565 (2.371)	2.897 (1.525)	1.287 (4.093)	0.76 (0.64 to 0.92)	0.004	0.74 (0.61 to 0.90)	0.002
x-comp FFCP	0.164 (2.730)	0.614 (1.438)	−1.569 (5.015)	0.41 (0.23 to 0.74)	0.003	0.40 (0.22 to 0.73)	0.003
x-comp FFP	1.829 (2.656)	2.135 (1.583)	0.648 (4.456)	0.58 (0.38 to 0.90)	0.014	0.59 (0.38 to 0.92)	0.021
x-comp FFPOP	2.869 (7.262)	2.105 (4.679)	5.810 (12.870)	1.64 (1.07 to 2.51)	0.023	1.67 (1.08 to 2.57)	0.020
Vx FFF	37.53 (122.57)	53.24 (75.57)	−22.97 (218.43)	0.50 (0.27 to 0.92)	0.027	0.51 (0.27 to 0.95)	0.033
Vy FFF	2093.7 (852.5)	2172.5 (756.3)	1790 (1117)	0.65 (0.42 to 1.00)	0.050	0.65 (0.42 to 1.01)	0.055
dy FFF	80.35 (16.24)	78.36 (12.49)	88.04 (24.98)	1.47 (1.12 to 2.77)	0.015	1.75 (1.09 to 2.80)	0.021
impulsM5	13.15 (7.20)	12.314 (6.697)	16.35 (8.25)	1.72 (1.13 to 2.61)	0.011	1.72 (1.13 to 2.64)	0.021
PMaxM5	119.3 (58.1)	113.1 (54.8)	142.96 (64.87)	1.66 (1.08 to 2.54)	0.020	1.68 (1.09 to 2.60)	0.019

*Odds ratio (OR) were adjusted for age and sex. †OR of an increased 1 SD. Mediolateral force ratios at first metatarsal contact (ratio FMC), forefoot flat (ratio FFF), initial contact phase (ratio ICP), mediolateral displacement of the centre of force (COF), velocity mediolateral displacement of the COF (Vx FFF), velocity anteroposterior displacement of the COF (Yx FFF), anteroposterior displacement of the COF at forefoot flat (dy FFF), absolute force–time integral underneath M5 (impulsM5), peak force underneath M5 (pMaxM5).

excessive pronation as well as insufficient pronation, may lead to complaints and LLOI. In this way, both abnormalities of the gait pattern may cause LLOI.

A limitation of this study is the fact that the subjects underwent plantar pressure measurements during barefoot running and the foot–shoe–ground interface was not taken into account (as running shoes might correct or even exacerbate deviant gait patterns). Nevertheless, we opted for barefoot instead of shod running because this condition permits focusing on intrinsic foot biomechanics without interference of different or unusual footwear. Willems *et al*[11] showed that intrinsic plantar pressure risk factors for ERLLP were less pronounced in shod compared with barefoot running. Therefore, those authors advised the use of barefoot running to be implemented first. The scope of this study was to investigate intrinsic gait-related risk factors for LLOI. The influence of shoe wear addresses the impact of an extrinsic factor on injury incidence. However, because runners train in shoes, shod running should be an area for further research to determine whether the identified risk factors are still related to the development of LLOI.

Clinically, the results of this study can be considered valuable for identifying individuals at risk of LLOI and suggest that effective prevention and rehabilitation of LLOI should include attention to the gait pattern and adjustments of altered foot biomechanics.

CONCLUSION

On the basis of plantar pressure measurements during barefoot running, the results of this study reveal some potential gait-related intrinsic risk factors for the development of LLOI: (1) a more laterally directed force distribution during initial contact phase, at first metatarsal contact and forefoot flat; (2) a more laterally directed force displacement in the forefoot contact phase, the foot flat phase and at heel-off, a delayed change of the displacement of the COF at forefoot flat and a highly directed anteroposterior force displacement of the COF at forefoot flat; and (3) a higher force and loading underneath the lateral border of the foot. These findings suggest that during gait, in this study, the subjects who developed LLOI had a heel strike in a less pronated position, and tended to roll off more on the lateral side of the foot compared with the uninjured group.

Competing interests: None.

Ethics approval: The study was approved by the ethical committee of the Ghent university hospital.

Patient consent: Obtained.

Provenance and peer review: Not commissioned; externally peer reviewed.

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