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Review

Plantar pressure measurements and running-related injury: A systematic review of methods and possible associations

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ABSTRACT

Pressure-sensitive measuring devices have been identified as appropriate tools for measuring an array of parameters during running. It is unclear which biomechanical characteristics relate to running-related injury (RRI) and which data-processing techniques are most promising to detect this relationship. This systematic review aims to identify pertinent methodologies and characteristics measured using plantar pressure devices, and to summarise their associations with RRI. PubMed, Embase, CINAHL, ScienceDirect and Scopus were searched up until March 2015. Retrospective and prospective, biomechanical studies on running using any kind of pressure-sensitive device with RRI as an outcome were included. All studies involving regular or recreational runners were considered. The study quality was assessed and the measured parameters were summarised. One low quality, two moderate quality and five high quality studies were included. Five different subdivisions of plantar area were identified, as well as five instants and four phases of measurement during foot–ground contact. Overall many parameters were collated and subdivided as plantar pressure and force, plantar pressure and force location, contact area, timing and stride parameters. Differences between the injured and control group were found for mediolateral and anteroposterior displacement of force, contact area, velocity of force displacement, relative force–time integral, mediolateral force ratio, time to peak force and inter-stride correlative patterns. However, no consistent results were found between studies and no biomechanical risk patterns were apparent. Additionally, conflicting findings were reported for peak force in three studies. Based on these observations, we provide suggestions for improved methodology measurement of pertinent parameters for future studies.

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1. Introduction

During the last four decades, running as a recreational activity has gained in popularity. Although we have experienced a surge in research on running and dramatic development in running shoes, there is no evidence to suggest that running-related injury (RRI) incidences are decreasing [1]. Various researchers using biomechanical analysis techniques have suggested possible risk factors of injury such as greater vertical loading rate and peak tibial shock [2], greater hip adduction, peak rearfoot eversion and peak absolute free moment of the tibia [3], reduced knee range of motion and reduced preactivation of tibialis anterior, rectus femoris and gluteus medius [4]. Traditionally, force platforms, motion analysis systems and electromyography have been used to assess these biomechanical characteristics of running in the laboratory. Accessibility to kinetic and kinematic measurement systems has increased greatly over the years. These devices are capable of three-dimensional force and marker coordinate measurement with immense precision and are generally considered the gold standard for force and joint angle measurements. Force platforms have been used in a number of studies on running biomechanics [2–4], but the measurements are generally confined to a particular location, often the laboratory. In addition, this setup measures only a single foot contact at a time [5] and can invoke "platform targeting" during overground running. Similarly, the analysis of several consecutive steps is generally not possible with motion analysis systems during overground running, and most published findings are based on an average of between 3 and 10 independent steps [6,7]. The use of instrumented treadmills can overcome these drawbacks, but the natural running pattern can be impacted [8]. Taken together, these elements could partly explain why there is still little consensus today on biomechanical risk factors for RRI. Additionally, these systems cannot provide

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information regarding the plantar loads and distribution of plantar pressures, which have been thought to provide valuable information in the study of specific pathologies and RRI risk factors [9].

Pressure-sensitive measurement tools have existed since the 1980s, and provide an alternative approach to studying the foot–shoe or foot–running surface interactions. They allow for the determination of centre of pressure trajectories during the contact phase of running and can provide data on plantar pressure location and magnitudes. Similarly to force platforms, pressure mats acquire data of a single step at a time, generally in the barefoot condition. Pressure treadmills and carpets are able to capture multiple, consecutive steps, yet remain laboratory-bound. Pressure insoles are inserted into the running shoe and provide insight into the vertical ground reaction forces and pressures acting within the shoe. Since insoles are portable devices, they can acquire data continuously and are not laboratory-bound.

With increasing focus on the relationship between shoe type and running biomechanics [10,11], insole-based sensors represent an interesting methodology that can be used to study the foot–shoe interactions [5,6] in the runner's habitual training environment. Insofar, these devices may aid to relate plantar pressures to RRI and have good potential to improve our understanding of RRI risk factors. So far we have witnessed a very heterogeneous approach by different laboratories when using pressure devices. Therefore, we conducted a systematic review of studies using pressure measurement systems, with the aim to identify pertinent methodologies and pressure-related characteristics measured using plantar pressure devices, and to summarise their associations with RRI.

2. Methods

We followed the PRISMA guidelines for this systematic review [12]. PubMed, Embase, CINAHL, ScienceDirect and Scopus were searched up until March 2015 using the following search terms:

(injur* OR running-related injur*) AND (pressure[MeSH Terms] OR pressure* OR centre of pressure* OR center of pressure* OR footstrike*) AND (running OR runner* OR jogg*)

Inclusion criteria of the initial screening of articles were as follows: RRI (pain in the lower limbs, resulting from and causing a reduction in running activity, and/or resulting in medical consultation) as an outcome measure, biomechanical analyses during running, retrospective case–control, prospective follow-up or randomised controlled trial study design and original data reported in any language. Studies on animals, cadavers, youths (<18 years old), orthotics, bracing/taping and case reports were discarded. The initial filtering of articles was performed by one of the investigators (RM), and an initial selection of articles was identified based on title and abstract. The remaining articles were screened by two investigators (RM and LM) independently based on title, abstract and if necessary, the full-text, selecting those articles which included RRI as an outcome measure, plantar pressure measurements during running and peer-reviewed articles (i.e. not conference abstracts, theses, book chapters). The reference lists of relevant articles were hand-searched for additional articles. All articles in the final selection compared an injury group with a control group.

A quality assessment of the articles fulfilling the above-mentioned criteria was carried out. The assessment tool used was an adapted version of an existing checklist put forward by Munn et al. [13]. This checklist was developed for non-randomised and non-intervention studies and deemed appropriate as no randomised control trials or intervention studies were found in this systematic review. A new item five was added to the checklist to distinguish between retrospective and prospective studies. The former introduces a greater risk of bias and confounding in their study designs. Therefore, a score of 1 was awarded to prospective studies, and 0 to retrospective study designs. Items 12 and 13 are concerned with how reliably RRI was determined and how accurately the pressure measurement systems could measure the parameters. Diagnosis of RRI by a medical professional resulted in a score of 1, whereas self-reporting RRI scored 0. Item 13 refers to the sampling rate of the pressure device, with a score of 1 awarded if it was reported to be greater than or equal to 100 Hz, as this has been reported to be the minimum sampling frequency required for accurate measurement of running biomechanics [14]. The quality was assessed by two of the authors individually, and any discrepancies in scores were discussed with and resolved by a third reviewer (DT) assigning a deciding score. We maintained the quality brackets of Munn et al. [13] with studies achieving an overall score of <60% being classed as "low", 60–74% as "moderate" and ≥75% as "high" quality studies.

Measurements obtained from injured runners and control groups were compared based on the standardised mean differences (SMD) determined from extracted means and standard deviations (SD) using the Review Manager (RevMan) [Computer program] (version 5.3. Copenhagen: The Nordic Cochrane Centre, The Cochrane Collaboration, 2014). SMDs (absolute values) were classified as large (≥1.2), medium (0.60–1.19) or small (<0.60) [15].

3. Results

After removing duplicates from the initial 1289 search hits, 811 studies were identified based on our search terms and through hand searching, 681 were excluded by one reviewer based on title and abstract, and two reviewers were unanimous on the final selection of eight studies for inclusion based on title, abstract and full text (Fig. 1). Of these eight articles, three are prospective follow-up studies including between 102 and 131 participants (Table 1). We must point out that although these were three independent studies, they all originated from the *Department of Rehabilitation Sciences and Physiotherapy* of Ghent University, Belgium. All three studies were concerned with novice runners from a start-to-run programme, and it is strongly believed that there was overlap of participants within these cohorts [16–18]. The other five studies are independent, retrospective, cross-sectional studies testing between 22 and 105 participants. Four studies used pressure platforms to collect their data, and the other four used insole devices. Three studies focused on Achilles tendinopathy, whereas the others focused on lower leg overuse injuries, patellofemoral pain, iliotibial band syndrome, 2nd metatarsal stress fractures and general running-related injuries. Five of the studies measured their runners on runways between 10 and 16.5 m, one study used a runway of 40 m, and the remaining two studies had their participants run on treadmills. Table 1 summarises the methodologies of the eight selected articles.

3.1. Quality assessment

Assessing the quality of the eight included articles resulted in one article being rated low quality (below 60% quality score), two articles rated as moderate quality (between 60 and 74% quality score) and five articles rating as high quality (above 75% quality score). The scores of each of the quality items are summarised in Table 2.

3.2. Division of plantar surface area

We identified five different subdivisions of plantar areas. For the purposes of this comparison, we will use universal terminology, to ensure clarity. The results from devices that provided high

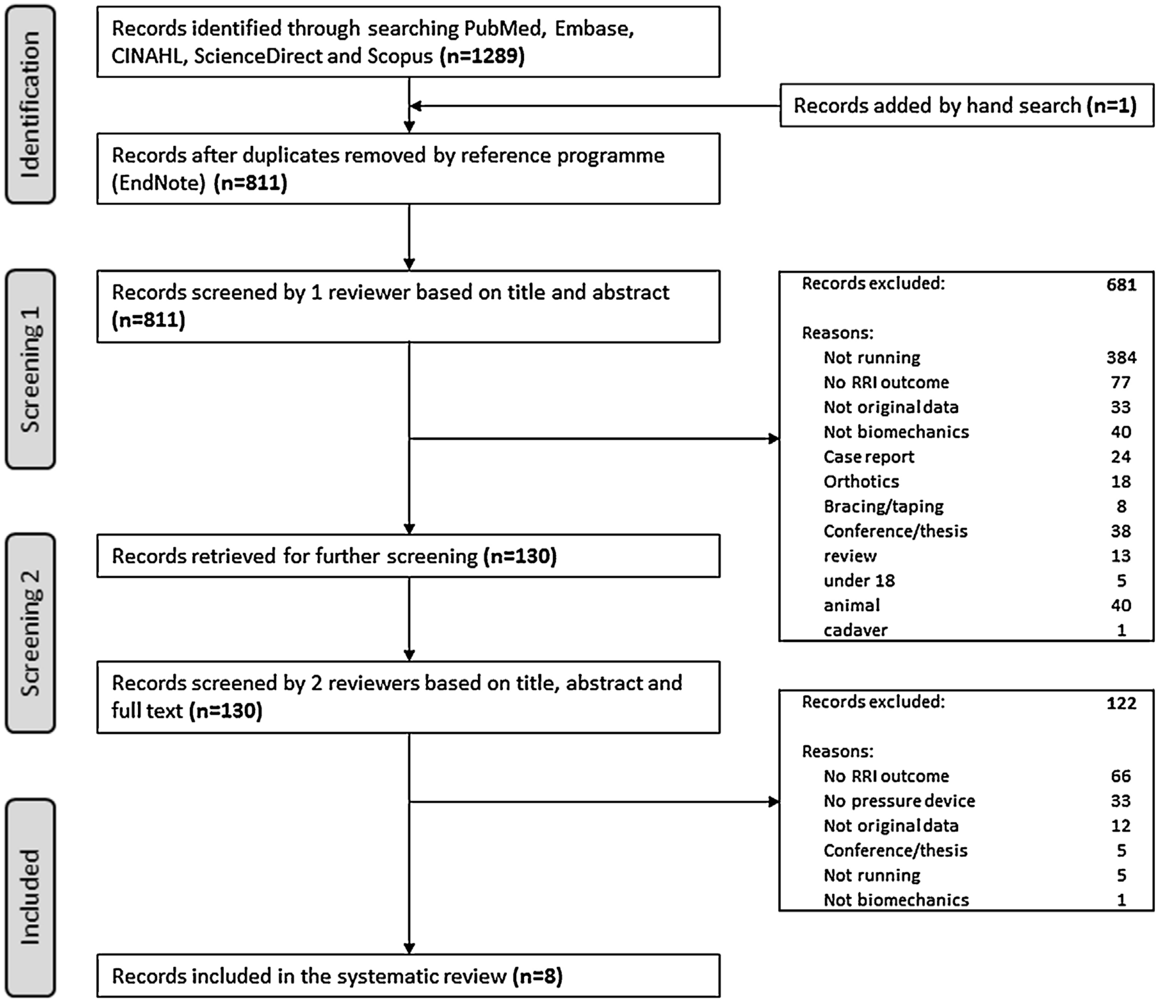

Fig. 1. Flowchart of article search and screening process.

spatial resolution were usually reduced in different anatomical zones, either by the software or the researchers, but information as to how this data reduction was achieved is incomplete. The Ghent University studies investigated eight plantar foot regions which did not take into account the entire surface area of the foot: medial rearfoot, lateral rearfoot, the five metatarsal heads and the hallux [16–18]. Grau et al. [19] divided into medial rearfoot, lateral rearfoot, medial midfoot, mid-midfoot, lateral midfoot, medial forefoot, mid-forefoot and lateral forefoot. Queen et al. [20] divided into the rearfoot, medial midfoot, lateral midfoot, medial forefoot, mid-forefoot, lateral forefoot, the hallux and the lesser toes. Ribeiro et al. [21] divided into medial rearfoot, mid-rearfoot, lateral rearfoot, the midfoot, medial forefoot and lateral forefoot. Mann et al. [22] used a prototype equipped with eight pressure sensors located at the medial rearfoot, lateral rearfoot, medial midfoot, lateral midfoot, the 1st, 2nd and 4th metatarsal heads and the hallux [23].

3.3. Parameter identification and comparison

We observed a diverse range of characteristics being measured between articles of different research groups. Table 3 provides an overview and description of these characteristics and groups them as plantar pressure and force, pressure and force location, contact area, timing and stride parameters. All the parameters, for which a significant difference between groups was found, as well as the corresponding SMDs, are presented in online supplementary Table 1. Concerning the Ghent University studies, these characteristics were measured at five instants and during four phases. These instants were: first foot contact (the instant the foot makes first contact with the surface), first metatarsal contact (the instant one of the metatarsal heads contacts the plate), forefoot flat (the instant all metatarsal heads contact the plate), heel off (the instant the heel region loses contact with the plate) and last foot contact (last contact of the foot on the plate). The phases were: initial contact phase (time between first foot contact and first metatarsal contact), forefoot contact phase, (time between first metatarsal contact and forefoot flat), foot flat phase (time between forefoot flat and heel off) and forefoot push-off phase (time between heel off and last foot contact). Overall, the studies included in this review reported findings specific to a particular plantar location, instant and/or phase making it extremely difficult to provide a comprehensive comparison of findings between studies, or indeed to conduct a meta-analysis on the data which exists at the moment.

As shown in Table 3, two studies investigated plantar pressure measurements, and no significant differences were found between previously injured and non-injured runners [20,21]. Three studies found peak vertical force to differ significantly between groups, however this was found at different plantar locations, with one study finding that higher peak forces predicted injury risk [17], and the other two studies finding that lower peak forces were

Table 1
Summary of methodologies for eight studies reviewed.

Author	Study type	Measurement protocol	Study population	Main outcome	Measurement tool
Thijs et al. [17]	Prospective, 10 week follow-up	15 m runway, barefoot jogging, 3 valid left and right trials, comfortable running speed	102 novice runners	Patellofemoral pain	Footscan pressure plate, 480 Hz (RsScan International)
Ghani Zadeh Hesar et al. [16]	Prospective, 10 week follow-up	15 m runway, barefoot jogging, 3 valid left and right trials, comfortable running speed	131 novice runners	Lower leg overuse injuries	Footscan pressure plate, 480 Hz (RsScan International)
Van Ginckel et al. [18]	Prospective, 10 week follow-up	15 m runway, barefoot jogging, 3 valid left and right trials, comfortable running speed	129 novice runners taking part in Start-to-run program. Injury free during last 12 months and not practicing other sports during the program.	Achilles tendinopathy	Footscan pressure plate, 480 Hz (RsScan International)
Baur et al. [24]	Cross-sectional, retrospective	Instrumented treadmill running at 12 km/h using RFS and gymnastic shoe and conventional shoe. Average of 10 steps per side.	8 experienced runners with chronic Achilles tendinopathy complaints and 14 controls. All had more than 3 h treadmill experience.	Achilles tendinopathy	Pedar Mobile System (Novel, Munich, Germany, 50 Hz)
Grau et al. [19]	Case–control, retrospective	13 m runway, barefoot running, average of 5 valid left and right trials, 3.3 m/s running speed.	18 iliotibial band syndrome patients, and 18 controls, male and female 18–50 years old, $\geq$20 km/week. No therapeutic interventions during last 6 months, previous knee operations, other injuries or problems at the lower extremities.	Illiotibial band syndrome	Pressure platform (Emed-X, 100 Hz, Novel GmbH, Munich, Germany)
Queen et al. [20]	Cross-sectional, retrospective	Standard running shoe on 10 m runway, 7 bilateral, valid trials, 3.3 m/s running speed	15 males, 15 control females and 9 females with stress fracture history between 18 and 35 years old, $\geq$10 miles/week, physically active for 1 h 3$\times$/week. Control groups no history of lower extremity stress fractures.	Second metatarsal stress fractures	Pedar-X plantar pressure measurement system, 100 Hz (Novel Inc., st Paul, Minnesota): insoles
Ribeiro et al. [21]	Retrospective	Standard running shoe 40 m runway and barefoot jogging, 3 valid left and right trials, 3.3 m/s running speed	45 recreational runners diagnosed with plantar fasciitis (30 with heel pain symptoms), 15 runners previous history of plantar fasciitis, and 60 controls.	Plantar fasciitis	Pedar X system, 100 Hz (Novel, Munich, Germany): insoles
Mann et al. [22]	Cross-sectional, retrospective	2 min acquisitions at 80, 90, 100, 110 and 120% of PRS on a treadmill.	44 running-related injury runners, 46 controls without performance-impeding conditions or pain due to injury at time of testing, comfortable with treadmill running, regular running for 6 of last 12 months, did not use orthopedic insoles and $>$18 years old.	Running-related injury	Runalyser (TNO, Eindhoven, The Netherlands), 250 Hz insole device

associated with injury [19,20]. One study found a greater relative force–time integral ($p = 0.006$; SMD = 0.93) at the lateral rearfoot in the injured group compared to a control group [19] (see also online supplementary Table 1).

The research group from Ghent University presented three studies focusing mainly on plantar pressure location [16–18]. Two of these studies found a more laterally directed force distribution during the forefoot flat phase in the injured group, according to the mediolateral force ratio [16,18]. One of these studies also found more laterally directed force distribution at first metatarsal contact ($p = 0.031$; SMD = 0.58) and more force displacement from medial to lateral during initial contact phase ($p = 0.047$; SMD = 0.43) in the injured group [16]. This same study also found more laterally directed (centre of force) CoF during forefoot contact and foot flat phase in the injured group [16]. One study found decreased total anteroposterior displacement of the CoF ($p = 0.015$; SMD = 0.94) in the injured group [18]. Although not stated as a measured parameter in the methods, a slower mediolateral ($p = 0.027$; SMD = 0.43) and anteroposterior ($p = 0.050$; SMD = 0.34) displacement of the CoF was reported in the injured group in one study [16]. A lower average distance of the CoP trajectory from the bisection of plantar angle (BPA) ($p < 0.001$; SMD = 0.85) was found in the injured group in one study of barefoot running [24].

The most commonly measured characteristic was contact time, measured in six studies, only one of which providing values of total foot–ground contact time [22]. No study found significant differences between the injured group and control group. A shorter time to vertical peak force at the lateral rearfoot ($p = 0.037$; SMD = 0.56) and medial rearfoot ($p = 0.016$; SMD = 0.46) relative to total contact time was found in the injured group [17]. When performing a stepwise, multi-variable logistic regression, these authors reported a shorter time to vertical peak force at the lateral rearfoot to be a predisposing factor of injury ($p = 0.048$) [17]. One study acquiring more than 150 consecutive strides at a time, found

Table 2
Quality assessment of the articles included in the review.

Article	The overall study quality								External validity	Internal validity-bias					Internal validity-confounding		Total Score	%	Quality Low <60% moderate 60–74% High >75%
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16			
	Hypothesis/ objective clear[1]	Injury and plantar pressure clearly described[1]	Characteristics of subjects described[1]	Distribution of principle confounders decribed[1]	Prospective design?[2]	Main findings clearly described[1]	Provide estimates of random variability[1]	Probability values reported for main outcomes[1]	Subjects asked to and willing to participate representative of entire population[1]	Blind measuring of the main outcomes[1]	Appropriate statistical test to assess outcomes[1]	Running-related injury reliably determined?[2]	Pressure parameters accurately measured?[2]	Did the protocol allow for representative analysis of the running pattern?[2]	Subjects (injured/ control) recruited from same population[1]	Adequate adjustment for confounding in the analyses [1]			
Thijs et al. [17]	1	1	1	1	1	1	1	1	1	0	1	1	1	0	1	0	13	81%	high
Ghani Zadeh Hesar et al. [16]	0	1	1	1	1	1	1	1	1	0	0	1	1	0	1	1	12	75%	high
Van Ginckel et al. [18]	1	1	1	1	1	1	1	1	1	1	1	0	1	0	1	0	13	81%	high
Baur et al. [24]	1	1	0	0	0	1	1	0	0	0	1	0	0	0	0	0	5	31%	low
Grau et al. [19]	1	1	1	1	0	1	1	1	1	0	0	1	1	0	0	0	10	63%	moderate
Queen et al. [20]	1	1	1	1	0	1	1	1	0	0	1	1	1	0	0	0	10	63%	moderate
Ribeiro et al. [21]	1	1	1	1	0	1	1	1	1	0	1	1	1	1	1	0	13	75%	high
Mann et al. [22]	1	1	1	1	0	1	1	1	1	0	1	0	1	1	1	1	13	81%	high

[1]Represents items taken from Munn et al. [13].
[2]Represents items which have been included specifically for this review.

that the injured group displayed more stride-to-stride correlation of strike index ($p = 0.046$; SMD = 0.27), yielding a less random strike pattern than their uninjured counterparts [22]. No other differences were found for timing or stride characteristics between the two groups in any study (Table 3).

4. Discussion

The aim of this systematic review was to identify variables, derived from pressure-sensitive measurement devices, which are of relevance for measurement in future research on RRIs. We found that comparing results of the selected articles was a complex process due to the use of many different characteristics and the subdivisions of plantar location and measurement time points and phases. This meant that any significant difference found between the injured group and the control group was very specific to a plantar location, a time point or a phase during stance. Therefore, it was virtually impossible to identify similar characteristics among the selected articles, and the reason for which a meta-analysis could not be performed. Overall, we identified five different methods of subdividing the plantar area, ranging between six and eight subdivisions. Based on distribution of plantar pressure findings and lower limb pathologies, devising a standardised subdivision of plantar pressure areas would greatly benefit future research using pressure devices. The subdivision of eight locations found in Mann et al. [23] provides almost complete coverage of the anatomical landmarks of the plantar foot. Nevertheless, a ninth sensor at the lesser toes would be useful to capture any pressure activity in this area during the pushing phase, e.g. when studying specific pathologies such as plantar fasciitis or Achilles tendinopathy. Finally, it should be noted that the multiplication of variables considered in the different studies supposedly had a type I error inflation effect.

4.1. Pertinent parameters

Analysing different anatomical regions of the foot separately can help link pressure patterns at these locations to specific pathologies. However, although several characteristics were measured in multiple studies, in most cases the present analysis did not identify any which were associated with RRI in more than one study. Also, only 1 of 20 parameters that were significant had large discriminatory power, all the other SMD were medium or small (Supplementary online Table 1). In the case of CoF, of the four studies measuring it, two found significant differences between groups, one in the mediolateral direction, and the other in the anteroposterior direction. In the case of peak force, this was found to be associated with injury, but studies were not unanimous in whether greater [17] or lower [19,20] forces in the injury group could be considered a risk factor (see online supplementary Table 1). Further study is required to shed more light on the role of peak force in injury occurrence. However, there is concern that pressure devices are not suited to measure force accurately, and further study to test the validity of such devices should be carried out. Indeed, to achieve a better understanding of how plantar pressure and force, plantar pressure and force location, contact area, timing and stride parameters are associated with RRI, replication studies are warranted and the clinical significance of the results needs to be analysed. Another important observation is that only two studies [20,21] focused on injuries located in the foot region (second metatarsal stress fractures and plantar fasciitis) while others focused on more proximally located injuries or RRI in general. One might speculate that plantar pressure measurements are more directly related to foot pathologies. However, the present findings are insufficient to support such consideration.

Table 3
Summary of characteristics measured using pressure-sensitive devices during running.

Characteristic measured	Unit	Description	Thijs et al. [17]	Ghani Zadeh Hesar et al. [16]	Van Ginckel et al. [18]	Baur et al. [24]	Grau et al. [19]	Queen et al. [20]	Ribeiro et al. [21]	Mann et al. [22]	Total number of studies measuring the parameter
Plantar Pressure and force											
Peak pressure	kPa or N/cm^2	Maximum pressure value during contact phase						NS	NS		2
Pressure impulse or pressure–time integral	KPa s	Area beneath the pressure–time curve							NS		1
Peak force	N or %BW	Maximum force value during contact phase	I > C[a]	NS	NS		I < C[b]	I < C[c]			5
Absolute force–time integral	N s	Area beneath the force–time curve ($\bar{x}$ Force × contact time)	NS	NS	NS			NS			4
Relative force–time integral	%	Absolute force–time × 100/sum of all force integrals	NS	NS	NS		I > C				4
Plantar pressure and force location											
Mediolateral force ratio		Sum of medial or lateral forces/the other	NS	I > C[d,e,f]	I > C[d]						3
Mediolateral displacement	Mm	Displacement of CoP/CoF at different instants or phases	NS	I > C[g]	NS	NS					4
Anteroposterior displacement	Mm	Displacement of CoP/CoF at different instants or phases	NS	NS	I < C[h]						3
Velocity of mediolateral/ anteroposterior displacement	mm/s	The speed of displacement of the *x*/*y* components of CoF		I < C[i]							1
Average distance from BPA to CoP trajectory	Mm	Area between CoP traj. and BPA normalised to foot length				I < C[j]					1
Strike index	%	Initial contact point expressed as % of total sole length								NS	1
Contact area											
Contact area	NICA or cm^2	Area of plantar surface (or section) in contact with ground						NS	NS		2
Timing parameters											
Contact time	s or ms	Time foot spends in contact with the running surface	NS	NS	NS			NS	NS	NS	6
Flight time	s or ms	Time of the swing phase								NS	1
Stride time	s or ms	Time between two successive foot contacts of same foot								NS	1
Duty factor	%	% of time foot spends in contact with the running surface								NS	1
Time to peak force	s or ms	Time between initial foot contact and maximum force	I < C	NS	NS						3

Table 3 (*Continued*)

Characteristic measured	Unit	Description	Thijs et al. [17]	Ghani Zadeh Hesar et al. [16]	Van Ginckel et al. [18]	Baur et al. [24]	Grau et al. [19]	Queen et al. [20]	Ribeiro et al. [21]	Mann et al. [22]	Total number of studies measuring the parameter
Stride parameters											
Stride length	M	Distance between two successive contacts of same foot								NS	1
Stride frequency	Stride/min	Number of strides per minute								NS	1
Stride variability	%	Coefficient of variation measured over a time series								NS	1
Inter-stride correlative patterns	α	Detrended fluctuation analysis of a time series								I>C	1

NS, a non-significant difference between groups was found; I < C, values are significantly lower in the injured group compared to the control group; I > C, values are significantly higher in the injured group compared to the control group; BW, body weight; CoP, centre of pressure; CoF, centre of force; NICA, units of normalised insole contact area; α, scaling exponent used to determine the extent of correlation or randomness of a particular variable between strides within a time series; BPA, bisection of plantar angle.

[a] Higher peak force at 2nd metatarsal with logistic regression analysis.
[b] Reduced peak force at medial forefoot in injured group.
[c] Reduced peak force at middle of the forefoot in injured group.
[d] More laterally directed force distribution at forefoot flat in injured group.
[e] More laterally directed force distribution at first metatarsal contact in injured group.
[f] More force displacement from medial to lateral during initial contact phase in injured group.
[g] More laterally directed CoF during forefoot contact and foot flat phase in injured group.
[h] Decreased total anteroposterior displacement of CoF in injured group.
[i] Both mediolateral and anteroposterior velocity of CoF displacement was lower at forefoot flat phase in the injured group.
[j] This was only the case when the CoP trajectory was located on the lateral side of the BPA.

4.2. Comparison of pressure devices

The studies included in this review either made use of pressure platforms or insoles. The fundamental differences between the two systems is that insoles measure pressure at the foot–shoe interface and can acquire multiple, consecutive steps. The latter feature is also possible with pressure treadmills and carpets, but to the authors' knowledge, these systems have not featured in studies on RRI. The measurement of consecutive steps allows analysing average measures, rather than data on a single, isolated step. Mann et al. [22] highlighted the advantages of measuring multiple steps, and conducted analyses on stride variability and stride-to-stride correlative patterns. Only one other study has looked at variability (of stride time) and correlative patterns between strides and its association with injury and found that previously injured runners displayed less correlation in stride time than non-injured runners [25].

When using a pressure platform, carpet or treadmill, participants must run barefoot if the aim is to get an idea of the pressure distribution on the plantar aspect of the foot. Such an approach may be particularly interesting when studying motion of different foot segments in combination with plantar pressure. However, it has been revealed that running barefoot is biomechanically different from running shod [26]. All studies in this review making use of pressure platforms acquired barefoot data. Two studies were not included in our final selection because they investigated injuries among physical education students and not strictly running injuries [27,28]. Both used a pressure platform and identical testing protocol, except that Willems et al. [28] measured using a shod condition. They reported less pronounced yet similar findings to their previous study using the barefoot condition, and concluded that the use of shoes when running over a pressure platform does not alter the identification of intrinsic risk factors of injury [28]. However, further study to support such a conclusion is warranted. Although barefoot running is gaining much interest in the running community and scientific literature [1,26], most people are not accustomed to running barefoot, questioning the representativeness of the data collected in studies requiring barefoot running for their analysis. On the other hand, using pressure platforms and testing runners while shod does not allow for the measurement of the interaction of the plantar surface of the foot and the shoe. This has been thought to be of greater interest in a running injury context than the shoe–ground interaction [5,6]. In this respect, pressure insoles appear to provide a series of advantages, as measurements may be performed outside the laboratory and participants do not need to target a platform when running overground. Additionally, the pressure insoles overcome the problem of multiple trials, they allow runners to run shod, and they measure at the foot–shoe interface. Therefore, the use of this new and fast developing technology that measures continuously the runners' biomechanics in their habitual training environment will undoubtedly provide new research opportunities in the future.

4.3. Study quality

It is apparent that there is room for improvement when it comes to the quality of studies to be conducted in the area of running injuries using pressure devices. Overall, the three prospective studies scored highly compared to the five cross-sectional studies. The retrospective study scoring "low" quality and the two scoring "moderate" quality had relatively small sample sizes, failed to analyse a representative running pattern, did not recruit the injured and control participants from the same population and did not provide adequate adjustment for confounding in their analyses [19,20,24]. These aspects should be fundamentally incorporated into future methodologies. Two studies were found to not have used appropriate statistical testing methods [16,19]. These studies included a large number of parameters in their analyses (see also supplementary online Table 1). The prospective study using a logistic regression model did not respect the guideline of 10 events (in this case an event being an injury) per tested factor, increasing the likelihood that findings are not a true representation of the association between parameters and injury [29]. Multiple testing was an issue in one retrospective study, increasing the risk of a type I error [19]. Furthermore those differences observed between groups from a statistical point of view may not necessarily have practical relevance given the size of the difference. To improve our understanding of which variables and what magnitude of difference must be observed between groups to ensure a clinically relevant finding, further prospective studies with large sample sizes should be conducted. We suggest a minimum sample frequency of 100 Hz, which was not the case for one study [24]. When analysing the characteristics of the strike pattern and timing parameters, high sampling frequencies are required to ensure data is accurately measured and to avoid confounding. Similarly, the spatial resolution of sensors should be taken into account, particularly when measuring direct pressure or force. When analysing the distribution of pressure over the whole foot plantar surface or over a specific area, higher resolution is needed and insoles with less than 10 sensors may not be adapted.

4.4. Future research

No randomised controlled trials were identified during the literature search within this study; such designs would provide valuable information on the causal effect of identified risk factors on RRI. We highlight the importance of high quality prospective designs, high numbers of participants and events of interest (i.e. injury events), and an a priori definition of relevant parameters to be tested. Mann et al. [22] suggested their lack of significant findings was in part due to using a global definition of running injuries. To be able to directly associate measured characteristics with specific pathologies, it is important that studies focus on one particular RRI type, as different injuries have different underlying mechanisms. With recent, rapid advancements in wireless data transmission, pressure sensor development, and wearable technologies, it is now time for researchers to conduct studies in the natural running environment of the recreational runner. This will shed more light on the interaction between running environment and biomechanics, and how this can influence the running style and, in turn, the risk of sustaining an injury. The quality assessment indicates the important aspects to be taken into account when preparing the methodology for RRI risk factor identification studies.

5. Conclusion

We identified studies attempting to relate plantar pressure and force, their location, contact area, timing and stride parameters to RRI. However, we were unable to observe any clear associations between these characteristics and RRI. CoF and peak force were measured by several studies but no unanimity of their relation to RRI was found. While further research is still warranted, continuous measurement in the natural running environment will help uncover the link between epidemiological study findings and biomechanical analyses. This approach will provide more complete and representative information to identify potential risk factors for specific RRI.

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Conflict of interest

None declared.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gaitpost.2016.03.016.

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