Foot strike determines the center of pressure behavior and affects impact severity in heel-toe running

Pieter Van den Berghe [1], Laurence Warlop [1], Rud Derie [1], Marc Leman [2], Dirk De Clercq [1], Bastiaan Breine [1]

[1] Department of Movement and Sports Sciences, Ghent University, Ghent, BE

[2] IPEM, Department of Arts, Music and Theatre Sciences, Ghent University, Ghent, BE

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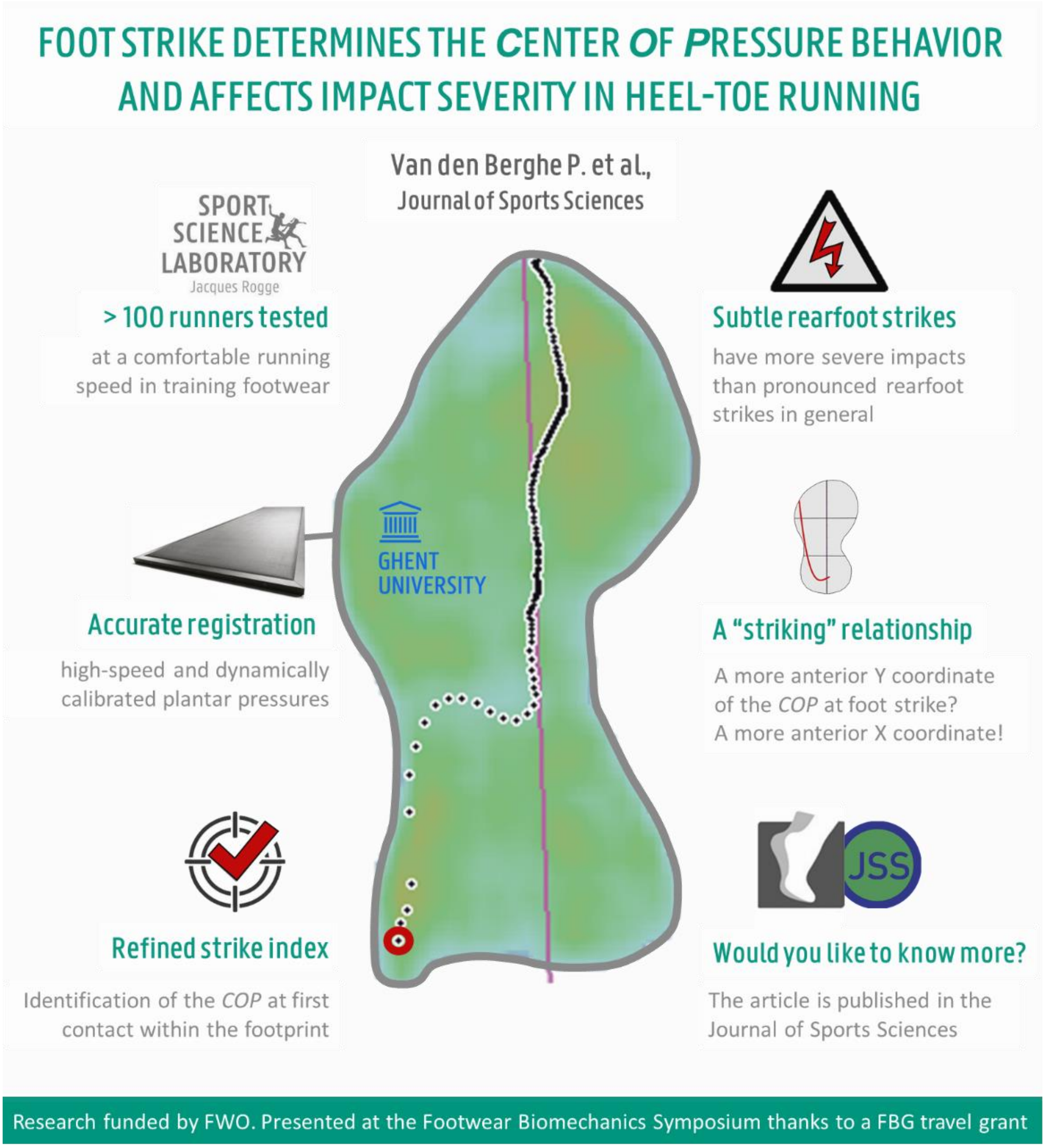


Abstract

This study assessed the center of pressure (COP) behavior and the relationship with impact severity during heel-toe running. We hypothesized the COP behavior depends on its location at foot strike, which would be associated with the vertical loading rate and peak tibial accelerations in heel-toe running. Ground reaction force and tibial acceleration were measured in 104 distance runners running level at ~3.2 m/s. High-speed plantar pressure captured at high temporal resolution (500 Hz) and spatial resolution (7.62·5.08 mm/sensor) allowed for localization of the COP directly on the footprint during running in self-selected athletic footwear. More lateral X-coordinates of the COP at first foot contact had, in general, more anterior Y-coordinates (adj.R^2:0.609). In heel-toe running, a more anterior foot strike had a greater refined strike index which was associated with a quicker roll-over in the rearfoot zone. This strike index contributed to greater maximum vertical loading rates (R^2:0.121), and greater axial (R^2:0.047) and resultant (R^2:0.247) peak tibial accelerations. These findings indicate that (1) the foot unroll is largely determined by the COP location at foot strike; (2) more anterior rearfoot strikes are more likely to have greater impact severity than pronounced posterior rearfoot strikes during shod running in conventional athletic footwear.

Introduction

The concept of center of pressure (COP) has been used to describe running gait (Cavanagh and Lafortune, 1980). At any instant during foot-ground contact, the COP is the location where the force vector would act if it had a single point of application (Cavanagh, 1978). In the seminal and influential paper of Cavanagh and Lafortune (1980), the authors presented the COP path obtained using a force platform during shod running. Although the apparatus has been commonly used to study the COP path during shod running (Cavanagh, 1978; Cavanagh and Lafortune, 1980), the localization of the COP at foot strike is not without error (Miller, 1990; Williams et al., 1987). Foot strike can be defined as the first contact between foot and ground and indicates the start of the foot roll-over. COP coordinates at foot strike have been reported outside the footprint record (Cavanagh and Lafortune, 1980; Miller, 1990). This error has been attributed to the initial positioning of the shoe (Cavanagh and Lafortune, 1980; Miller, 1990), which is not reliably detected by force platforms when very small ground reaction force is at play (Williams et al., 1987). An objective and automatic determination of strike index can be difficult due to the erratic nature of the early COP path when noise levels are relatively high and division by very small numbers is being performed in the calculation (Bobbert and Schamhardt, 1990; Williams et al., 1987). Williams & Cavanagh (1987) dealt with this issue by defining the strike index at the instant when the vertical ground reaction force reaches 10% of its maximum value during foot-ground contact. This classic method of strike index determination is problematic because the foot is already experiencing a certain amount of loading and may have made midfoot contact by this point in some runners. The utilization of a high-speed plantar pressure system could improve the study of the COP under very small vertical force. For instance, the sensor technology of a Footscan system can localize the COP directly on the plantar footprint at the instant of first foot contact with a high spatial resolution (7.62 · 5.08 mm per sensor) (RSscan International, 2014). The Footscan sensors come with a factory calibration and dynamic trial-by-trial calibration is feasible by mounting the pressure plate on top of a force platform of similar size. The simultaneous registration of plantar pressure and vertical ground reaction force permits to properly study COP coordinates from the instant of first foot contact to toe-off (Breine et al., 2014; De Cock et al., 2005; Willems et al., 2007). The latter gait event indicates the end of the foot roll-over. In the present paper, dynamically calibrated plantar pressures are measured to study the COP behavior of different foot strikes in a large cohort running shod.

Exemplary COP paths of different foot strikes have been described in previous research involving shod running (Breine et al., 2017c; Cavanagh and Lafortune, 1980). Cavanagh and Lafortune (1980) noted substantial variability exhibited in the COP behavior at foot strike. This variability has been reduced by converting continuous COP data to categorical groups of foot strike patterns (Breine et al., 2017c, 2014; Cavanagh and Lafortune, 1980; De Cock et al., 2005; Larson et al., 2011; Willems et al., 2007). In the mean COP pattern for classified rearfoot strikes, the COP coordinates started on the rear lateral border of the shoe and moved in anteriorly after foot strike (Cavanagh and Lafortune, 1980). Breine et al. (2014; 2017) further categorized the rearfoot strikes in which the time required by the COP to make first metatarsal contact was a main discriminant between the two subgroups. The subgroup of rearfoot strikes with less time of first metatarsal contact was characterized by a COP occurring more lateral at first foot contact. The COP at first foot contact of midfoot strikes occurred at approximately half of shoe length and more lateral to the midline of the footprint (Cavanagh and Lafortune, 1980). That of the group of forefoot strikes occurs in the front one-third of the foot and likely more lateral than in the other foot strike pattern groups. Categorization of foot strikes has been common practice (Breine et al., 2017c, 2014; Cavanagh and Lafortune, 1980; De Cock et al., 2005; Willems et al., 2007), but one may seriously underestimate the extent of variation in outcome between groups and considerable variability may be subsumed within each group (Altman and Royston, 2006). Categorization has concealed relationships between spatial (e.g., COP coordinates at first foot contact) and temporal (e.g, time of first metatarsal contact) variables of the COP in shod running so far. Instead of categorizing continuous variables, we prefer to keep them continuous to evaluate a relationship. In exemplary COP trajectories it appears the COP's location at the instant of first foot contact roughly follows the curvature of the shoe sole (Breine et al., 2017c; Cavanagh and Lafortune, 1980), with a more lateral coordinate to a forefoot strike from a rearfoot strike. Hence, the relationship between the XY coordinates of the COP at foot strike may be non-linear across the foot strike continuum and should be evaluated as such.

Epidemiological studies of runners have investigated measures of impact severity as a factor associated with running-related injury (e.g., Futrell et al., 2018; van der Worp et al., 2016). For example, a meta-analysis concluded that groups of heel-toe runners with a history of tibial stress fracture had a greater magnitude of vertical loading rate than groups without a running-related injury (van der Worp et al., 2016). The vertical loading rate has also discriminated between groups of injured and uninjured runners, though the association between the instantaneous peak vertical loading rate and running-related injuries only reached statistical significance in heel-toe running (Futrell et al., 2018). Specific to heel toe-running is the rearfoot strike, meaning the rear one-third of the foot contacts the ground first. If rearfoot strikes are continuously distributed, as postulated by Shorten & Pisciotta (2017), continuous data analysis is preferred to study the foot-ground interaction and the relationships with measures of musculoskeletal loading. Retaining high resolution is required to understand the true relationship between foot strike pattern and impact severity. For example, a flatter foot position at touchdown has been correlated to a greater vertical loading rate in heel toe running (Breine et al., 2017c). Therefore, it may be the COP at first foot contact contributes to the magnitude of the vertical loading rate. The vertical loading rate is derived from the vertical component of the ground reaction force. However, the use of ground reaction force measurements to evaluate the severity of impact at the lower extremity is limited by the nature of the force platform itself (Shorten and Mientjes, 2011). The force platform output reflects the average acceleration of the whole body and is not specific to the lower extremity (Shorten and Mientjes, 2011). Lightweight accelerometers can be taped distally on pre-stretched skin of the lower leg to capture acceleration of the lower extremity in a non-invasive manner (Laughton et al., 2003; Van den Berghe et al., 2019b). Tibial acceleration quickly increases following the first foot contact because the leg suddenly slows down and reaches a peak magnitude during the impact phase (Van den Berghe et al., 2019b). Hence, peak tibial accelerations may be a more local indicator of the severity of impact to the lower extremity. Given that the vertical loading rate has been correlated with axial and resultant peak tibial accelerations in heel-toe running (Laughton et al., 2003; Van den Berghe et al., 2019b), it is expected that peak tibial accelerations would also be affected by the COP at first foot contact.

This study assessed the COP behavior in a large group of shod distance runners and the relationship of the COP at foot strike with impact severity during heel-toe running. We hypothesized the foot unroll to depend on the COP location at first foot contact, which would be associated with the vertical loading rate and peak tibial accelerations during heel-toe running. Therefore, we evaluated whether there exists (1) a positive relationship between the XY coordinates of the COP at first foot contact along the foot strike continuum; (2) a negative relationship between a refined strike index (i.e., COPy at first foot contact) and the time to first metatarsal contact in the rearfoot strikes; (3) a positive relationship between a refined strike index and the impact magnitudes in the rearfoot strikes.

Methods

Study design

Cross-sectional lab study

Participants

One hundred and four Caucasian runners (sex: 57 male and 47 female, stature: 1.73 ± 0.09 m, body mass: 68.8 ± 11.8 kg, age: 36.5 ± 9.5 years, mean ± std. deviation) volunteered for a shod running session after providing written informed consent. All were interested to participate in a running program and were recruited via word of mouth and advertisements on social media and specialized websites. Our sample size was identical to that of Pataky et al. (2012) who studied plantar pressure patterns in a large sample of subjects during walking. Participants were between 18 and 60 years old, free of running-related injury for the past 6 months, typically ran at least twice a week, and did not train in minimalist footwear. Three participants reported minor complaints in the months preceding the running session, but this did not hamper them from training. Data collection occurred between October 2017 and February 2019. This study was approved by the university's institutional review board.

Protocol

Participants entered the biomechanics laboratory in their conventional sportswear and self-selected, accustomed, athletic footwear. We equipped the participant with sensors while he or she was filling out a questionnaire about their running habits. Thereafter, the participant walked shod along the instrumented runway, which was located in a straight section of a running loop (Figure 1). Subsequently, the participant started running at a self-selected speed. A warm-up period of 5 minutes served as a familiarization to the experimental setup. Thereafter, the participants continuously ran on the indoor track at a pace of 3.2 ± 0.2 $m \cdot s^{-1}$, which was identical to the running speed chosen by Breine and colleagues (Breine et al., 2017c, 2014) and has been a common speed range to evaluate endurance running. Speed feedback was given verbally by a test leader when the running speed of a trial was outside the speed boundary.

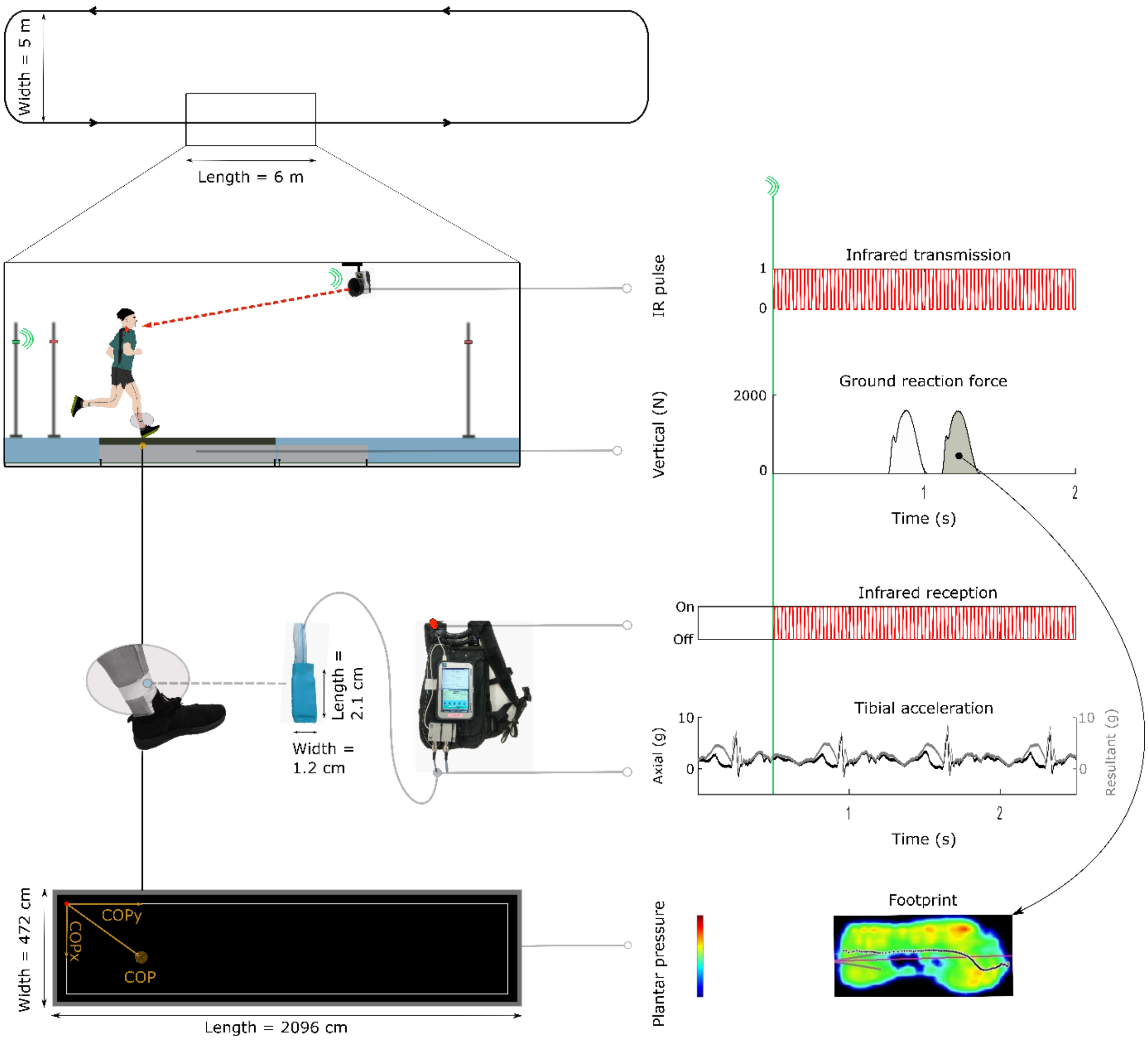


Figure 1. Schematic representation of the set-up in the laboratory: running course, measurement zone, measurement instruments and signals.

Measurements

Plantar pressure

Dynamic pressure measurements of shod locomotion were performed using a Footscan pressure plate (length x width x height: 2096 x 472 x 18 mm, mass: 28.8 kg, pressure range: 1 – 127 N/cm²). The plate was flush with the floor and was positioned approximately in the middle of a straight section of the running loop (Figure 1). The Footscan system (RSscan International, Olen, Belgium) registered high-speed pressure data when the subject walked (126 Hz) or ran (500 Hz) in his/her training shoes over the 2m plate. The plate measured plantar pressure using an X-Y matrix of resistive pressure-sensitive sensors. The active sensor area was 1950 · 325 mm (RSscan International, 2014). The number of sensors was 16384 and the sensor dimensions of the non-square measurement grid were 7.62 mm · 5.08 mm, which gives a sensor density of almost 3 sensors per cm². The pressure plate was scanned sequentially in the walking condition and simultaneously in the running condition. The sequential mode has been recommended when a double stance phase is expected and was therefore applied in the walking condition (RSscan International, 2014). The simultaneous mode has been recommended for aerial running because of the single stance phase (RSscan International, 2014).

Prior to data collection, the pressure plate was sent to the manufacturer for replacement of the pressure-sensitive layer and factory calibration. The protective top rubber layer on the 2 m Footscan plate contained a mixture of natural dry rubber and synthetic rubber, which is suited for the analysis of locomotor activities. The undercoating of the plate was sealed by tape to a strain-gauge force platform of similar length and width (ZBP460x2 070-1000, Advanced Mechanical Technology, Inc., Watertown, MA) for a specific application. The signal of the vertical force from the 2 m AMTI platform was used to dynamically calibrate the measurements of the Footscan system on a trial-by-trial basis, which enabled correcting the pressure frame using the vertical force from the force platform and was done frame by frame. So, this procedure permitted continuous calibration of the total vertical force registered by the pressure plate at every measurement time point by using the total vertical force of the force platform at that time point. This approach has been used in animal and human studies (Breine et al., 2017c, 2014; De Cock et al., 2005; Oosterlinck et al., 2012; Van den Berghe et al., 2019b; Willems et al., 2007), and is recommended for research purposes (Wilssens, 2010).

Each time the Footscan software (v7.105) was launched, the pressure offset was determined when there was nothing on the pressure plate and the threshold of the pressure plate was adjusted according to the offset value. When a participant passed the start line of the loop made in the biomechanics laboratory (Figure 1), we initiated a measurement and the plate started scanning. A 2-s data recording started when the overall pressure reached the preset threshold level. Footscan 7 automatically recognizes feet when recording the dynamic measurement. A masking procedure was initiated during foot detection that determined the location of ten anatomical zones. With this feature, the pressure under the foot can be linked to the anatomical zones. During shod running, it is impossible to overlay zones on the detected metatarsal heads as in the barefoot condition (Willems et al., 2007). Therefore, the software applies a scalable anatomic foot mask through which the analyzed surface underneath the anatomic regions of interest were enhanced (Breine et al., 2014; Willems et al., 2007). Determination of the anatomical zones was needed to determine the foot axes. The longitudinal foot axis was situated between the medial and lateral part of the heel and between the second and third metatarsal heads (Breine et al., 2014; RSscan International, 2014; Willems et al., 2007). We verified the automatic detection and assignment of the longitudinal foot axis. A manual adjustment of the foot axis was made if deemed necessary, which usually happened when part of the rearfoot zone was absent in a foot-ground contact.

Vertical ground reaction force

A straight section of the oval track was embedded with two of the proven force platforms available commercially (2.1·0.5-m and 1.2·1.2-m, AMTI, Watertown, MA) to capture the ground reaction force (Figure 1). These platforms were independently mounted on mounting rails that were bonded to a concrete floor and positioned in series near the middle of the 30 m runway. The force platforms were covered. One cover had an identical color of the sports flooring to avoid targeting of the platform (MultiFunctional, Herculan Sports, the Netherlands). The pressure plate was mounted underneath the other force platform and covered it. The signals were recorded at 1000 Hz and transmitted to a DAQ in connection with a computer. The signals from the force platform underneath the pressure plate were split to the 3D interface box of the Footscan system. This box transmitted the data from the force platform for dynamic calibration in Footscan 7.

Tibial acceleration

We intended to measure the tibial acceleration as accurately as possible in a non-invasive manner. Therefore, a small body-worn sensor was employed and multiple methodological precautions were taken. The participant's skin was pre-stretched at ~8 cm above the left and right medial malleolus with the intention to improve the mechanical skin-to-bone coupling. Two lightweight, low-power, three-axis, MEMS accelerometers (LIS331HH, STMicroelectronics, Genèva, Switzerland; 1000 Hz/axis; sensor weight: 0.020 grams; range: ±24 *g*) were utilized. Each accelerometer was fitted in a heat-shrinkable instead of a plastic case to minimize the total mass. The sensor and wrap were considered lightweight because the total mass was less than 3 grams. A test leader visually aligned the axial axis of the accelerometer with the lower leg's longitudinal axis before its mounting. The sensor was firmly taped to the anteromedial distal aspect of each lower leg by utilizing non-elastic tape (Laughton et al., 2003; Van den Berghe et al., 2019b). The non-elastic zinc oxide tape (4 cm width, Strappal, BSN) was tightly fastened to the limit of subject tolerance. The accelerometers were wired to a microprocessor (Teensy 3.2), which was encased in a plastic casing that was laced to the shell of a backpack stripped from compartments. The participant wore a backpack system (mass: 1.6 kg) to collect tibial acceleration and infrared light data on the body. The raw sensor data were transmitted through serial over USB to a 7-inch tablet (Roughpad FZ-M1, Panasonic) mounted on the backpack's shell. The accelerometer was powered by the battery of the tablet to use the least amount of power possible. The tablet was remotely controlled by a nearby PC over the Wi-Fi network. When the participant started a new loop in the laboratory, a mobile application was executed on the tablet to capture tibial acceleration and infrared signals (Van den Berghe et al., 2019b).

Infrared light

An infrared phototransistor (Fairchild Semiconductor IR phototransistor QSE113) was also wired to the microprocessor. As a result, tibial acceleration and infrared pulses were simultaneously registered at 1000 Hz. The infrared sensor was affixed to a shoulder strap of the backpack. The positioning of the sensor on the backpack's strap enabled the receipt of infrared light in proximity of the participant. After the participant ran 13-m along the runway, a passive optical motion capture system was activated (Figure 1). The infrared signal transmitted by the motion capture cameras was detected by the infrared phototransistor worn by the runner. The onset of the infrared transmission of the cameras marked the start of the force recording. This mark in time is useful for time synchronization of the tibial acceleration and force data, even though the measurement systems registered independently. This measurement approach, with the capture of the first infrared light of the camera by the phototransistor on the body, allowed to synchronize the vertical ground reaction force and tibial acceleration data up to millisecond precision in time (Van den Berghe et al., 2019b).

Running speed

Timing gates were situated 6 m apart and used to determine the running speed in the measurement volume (Figure 1). The running speed was shown on an LCD screen in front of the test leaders on a trial-by-trial basis trial. A measurement was discarded if the running speed was outside the instructed boundary.

Training habits, footwear characteristics, and perceived foot contact type

The training habits (i.e. training frequency) and footwear characteristics of the participants were obtained through an online questionnaire. An indication of common footwear characteristics (heel-to-toe drop, heel stack height) was ascertained from online databases (Running Shoes Guru, Solereview, Runner's World, etc.). A self-assessment of the foot contact type was performed such that each participant indicated if first foot contact was made on the heel or not.

Data analysis

Initial contact phase

A reference dataset was created by analysis of the first left footfall and the first right footfall that made full contact with the pressure plate. The footfalls completely contacting the plate occurred consecutively in the same lap or non-consecutively, and then originated from different laps. The analysis of one pair of footfalls is a realistic scenario when large groups of runners are studied (Larson et al., 2011; Shorten and Pisciotta, 2017). The COP at a measurement time point was computed from the distribution of forces to an area of contact on the surface of the pressure plate. Distinct instants of foot roll-over were determined for each trial based on the peak pressure footprint. First foot contact was defined as the instant the foot made first contact with the pressure plate (De Cock et al., 2005; Willems et al., 2012), meaning the first pressure was registered. During the foot roll over in heel-toe running, the first metatarsal contact has been defined as the instant when one of the metatarsal heads contacted the pressure plate (De Cock et al., 2005; Willems et al., 2012), meaning a metatarsal zone became visible. The initial contact phase starts with first foot contact and ends at first metatarsal contact (De Cock et al., 2005; Willems et al., 2012). The duration of this phase indicates the time to first metatarsal contact and has been reported as a percentage relative to the total roll-over time (Breine et al., 2014). Following registration and masking, the COP and the timing information were exported using the default export setting. The COP paths of the right foot contacts were mirrored during the export process. The displacement of the COP line was exported frame by frame (Breine et al., 2014; RSscan International, 2014). The displacement of the COP line in posterior-anterior direction (Y) with respect to the Y–axis coincided to the foot axis and with the according time (ms) and force (N) (RSscan, 2009). So, the Y values are expressed relative to the foot axis (Breine et al., 2014; Willems et al., 2007). The X-axis was perpendicular to the longitudinal foot axis and its values are expressed relative to that axis. The X-coordinates of the COP were determined by the Footscan software, were negative when they are positioned laterally to the longitudinal foot axis, and were normalized to the shoe width (mean: 106 ± 9 mm). The length of the outer shoe sole was approximated by the longitudinal length of the outer sole derived from the walking condition (Figure 2). For normalization to shoe length (mean: 306 ± 19 mm), we assumed that the most distal COP coordinate was at the total foot length (Breine et al., 2014). The value of the normalized COP's Y-coordinate at first foot contact was defined as the refined strike index. This index is a dimensionless quantity between 0 and 1 that indicates the region of first contact on the shoe sole (Breine et al., 2014). A footfall was identified as a rearfoot strike (0 ≤ refined strike index ≤ 0.333), a midfoot strike (0.333 < refined strike index ≤ 0.666), or a forefoot strike (refined strike index > 0.666) (Breine et al., 2014). The classic strike index was also calculated to illustrate differences between the strike index derived from force data and the refined strike index derived from plantar pressure data (Figure 3). The calculation of this index was based on the COP position when the vertical ground reaction force of the force platform reached 10% of maximum force. The rearfoot strikes imply heel-toe running and were further analyzed. The time of first metatarsal contact was extracted from the timing information contained in the Footscan software.

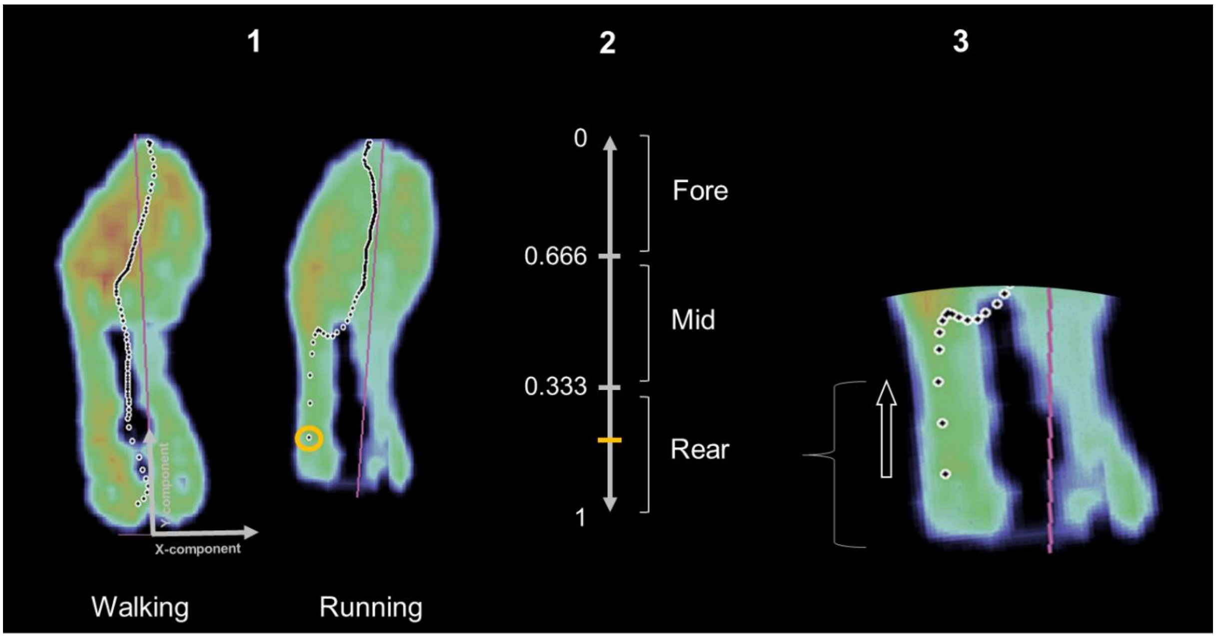


Figure 2. The process of foot contact analysis. (1) Read the COP path of the walking and running trials. (2) Compute the refined strike index of the running trial. (3) Extract the time of first metatarsal contact in the rearfoot strikes

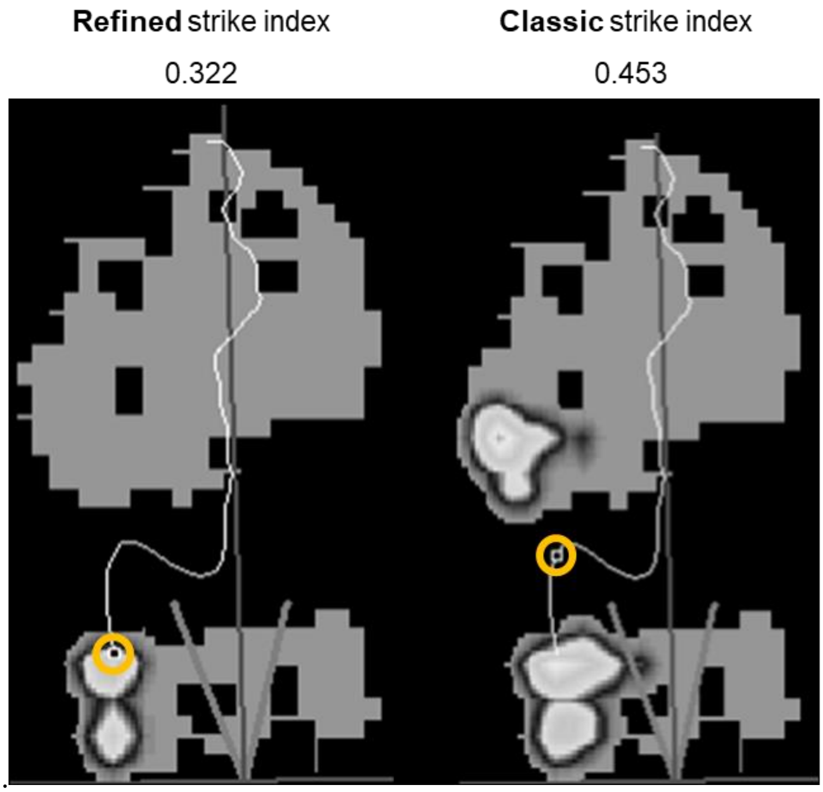


Figure 3. Example of the difference between the refined and classic methods to determine the foot strike index. Each image shows the pressure measured at a particular instant of the foot roll-over. The refined strike index is computed at the instant of the first foot contact, whereas the classic strike index is determined when the vertical ground reaction force has reached 10% of its maximum during stance.

Impact characteristics

The first five left and right foot contacts were collected, which resulted in a total of ten trials per subject for determining the impact characteristics. The tibial acceleration and ground reaction force measurements of the first left and right contacts were aligned with that of the plantar pressure measurements. The additional foot contacts were included to ensure reliable values in impact magnitudes. Previous research has shown that four trials can result in excellent intraclass correlation coefficients for the peak tibial accelerations and vertical loading rate when measured with similar equipment in the same running environment (Van den Berghe et al., 2019b), indicating low inter-trial variability for these variables. Force data registered in the Qualisys software application Track Manager were exported. Tibial acceleration and infrared data registered in the mobile application were also exported. These files were imported to MATLAB by running custom scripts (Van den Berghe et al., 2019b). The vertical ground reaction force and the tibial accelerations were synchronized in time based on the infrared pulse that indicated the start of the force measurement. This synchronization process allowed to extract the time series of tibial acceleration during stance. These data were low-pass filtered using a zero-lag second-order Butterworth filter with a 60 Hz cut-off frequency. The maximum instantaneous vertical loading rate of the ground reaction force (Breine et al., 2014), the axial peak tibial acceleration, and the resultant peak tibial acceleration were calculated (Van den Berghe et al., 2019b). The resultant peak tibial acceleration was defined as the maximum of the vector norm. Stride frequency was derived from the time between the axial peaks.

Statistics

The normalized XY coordinates of the COP at first foot contact were inputted in a cubic regression model expressing the Y coordinate as a function of the X coordinate (JASP R-module; JASP Team, Amsterdam, the Netherlands). Pearson correlation evaluated whether there is statistical evidence for a linear relationship between the refined strike index and the time of first metatarsal contact in the rearfoot strikes (JASP 0.14.0). The correlation coefficient *r* has been applied as a way to infer correlation such that $r \leq 0.35$ represent low or weak correlations, $0.36 < r \leq 0.67$ indicate modest or moderate correlations, $0.68 < r \leq 0.89$ indicate high correlations, and $r \geq 0.90$ suggests very high correlations (Taylor, 1990). If significantly correlated with an impact characteristic, the refined strike index was used to construct a linear regression model. An impact characteristic was treated as a continuous dependent variable (Breine et al., 2017c).

Results

The mean refined strike index was 0.189 ± 0.128 (mean ± std. deviation) and ranged between 0.058 (minimum) and 0.764 (maximum) across all foot contacts. The instant of first foot contact was detected at 25 N (median) in vertical ground reaction force and the interquartile ranged from 6 N to 49 N. Ninety-nine of the 104 participants demonstrated a habitual rearfoot strike in at least one of both sides. They typically ran 33.6 ± 16.2 km/week and their self-reported running speed during practice was 3.0 ± 0.3 m/s. Their shoe size was 41 ± 3 EU with a stack height of 27 ± 5 mm and a heel-toe offset of 9 ± 2 mm. Their stride frequency was 1.40 ± 0.07 Hz at the running speed of 3.22 ± 0.06 m/s. We identified 192 rearfoot strikes in the 208 foot contacts analyzed, leading to a prevalence of 92.3% in this cohort of distance runners. Midfoot strikes were observed in 5.3% and forefoot strikes in 2.4%. In contrast, only 32% of the cohort reported themselves as "heel strikers". Of particular interest is the variability exhibited in the movement of the COP in the posterior part of the shoe during heel-toe running in regular athletic footwear (Figure 4). In the sample of heel toe runners, the refined strike index ranged from 0.058 to 0.329 (0.152 ± 0.051) and the time of first metatarsal contact ranged from 1.5% to 20.5% (9.6 ± 3.8%) of the foot-ground contact time in the rearfoot strikes. In 10% of the rearfoot strikes we noticed the refined strike index was less than 0.333 and the classic strike index was greater than 0.333. This misidentification of pseudo-midfoot was due to a refined strike index of approximately 0.200 or more and a very fast anterior progression of the COP in the rearfoot zone that progresses to the midfoot zone in 5% of the foot-ground contact time or less (Figure 3). Video fragments of trials showing a rather slow and a rather fast first metatarsal contact are included as Supplemental material (Supplementary videos 1-3). Supplementary video 3 shows first metatarsal contact at half the time of that in supplementary video 2. The individual differences are chiefly expressed by varying pressure distributions from the rearfoot zone to the midfoot zone of the shoe. Video 3 is a frame-by-frame extract of video 1 and shows the dynamic pressures during the initial contact phase of the foot roll-over in heel-toe running (Supplementary video 5).

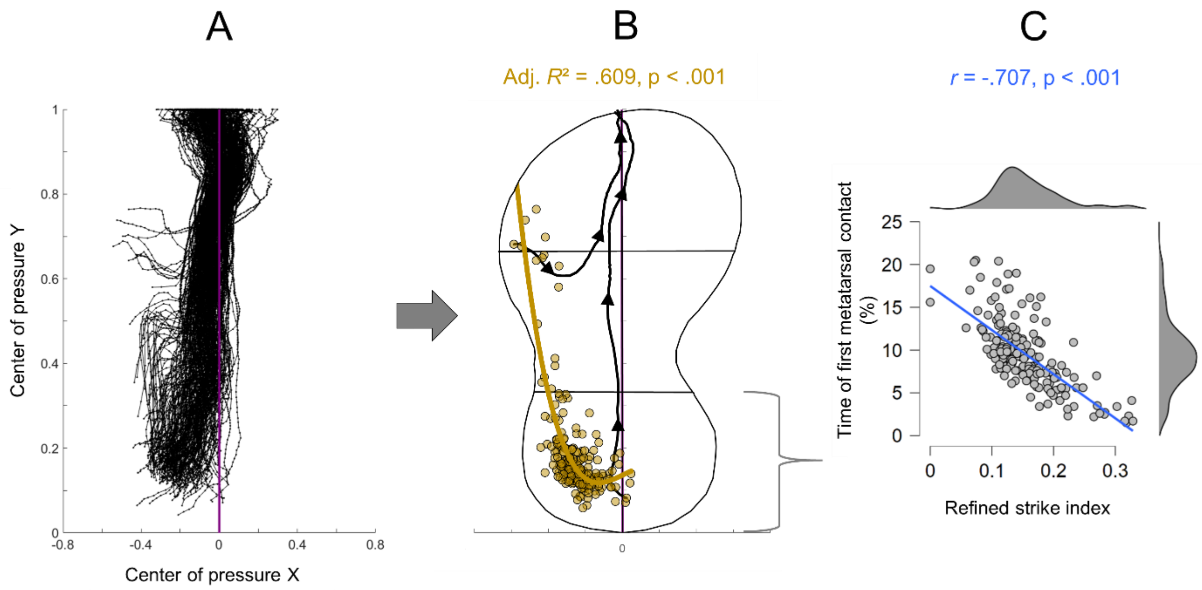


Figure 4. [A] Center of pressure paths of all footprints. The black curves represent the COP displacement during foot-ground contact. The purple line in the middle indicates the longitudinal foot axis aligned with the vertical. [B] The orange curve shows the relationship between the COP coordinates at first foot contact. The XY coordinates at first foot contact are plotted in orange for each of the foot contacts. Exemplar COP paths of foot strikes at both ends of the continuum are plotted on an illustrative footprint. Directions are indicated with a symbol ▲ at random instants of time. [C] The relationship between the refined strike index and the time of first metatarsal contact in the rearfoot strikes.

The cubic model was able to explain the Y-coordinate of the COP at first foot contact with an adjusted R^2 of 0.609 (p < 0.001). Supplementary table S1 gives the model's goodness of fit. A more anterior footstrike (i.e., a greater refined strike index) was related to a more laterally localized COP at first foot contact (Figure 4). The refined strike index and the time of first metatarsal contact represent a correlation coefficient (r = -0.707, p < 0.001, 95% CI = [-0.771, -0.627]) which was significantly (P < .05) different from zero (Figure 5). The high negative correlation indicates an inverse relationship whereas the refined strike index increases, the time of first metatarsal contact decreases during heel-toe running. The refined strike index was a significant predictor of the vertical loading rate (R^2: 0.121, p < 0.001), the axial peak tibial acceleration (R^2: 0.047, p = 0.003), and the resultant peak tibial acceleration (R^2: 0.251, p < 0.001). Figure 5 visualizes the scatter between the explanatory and outcome variables.

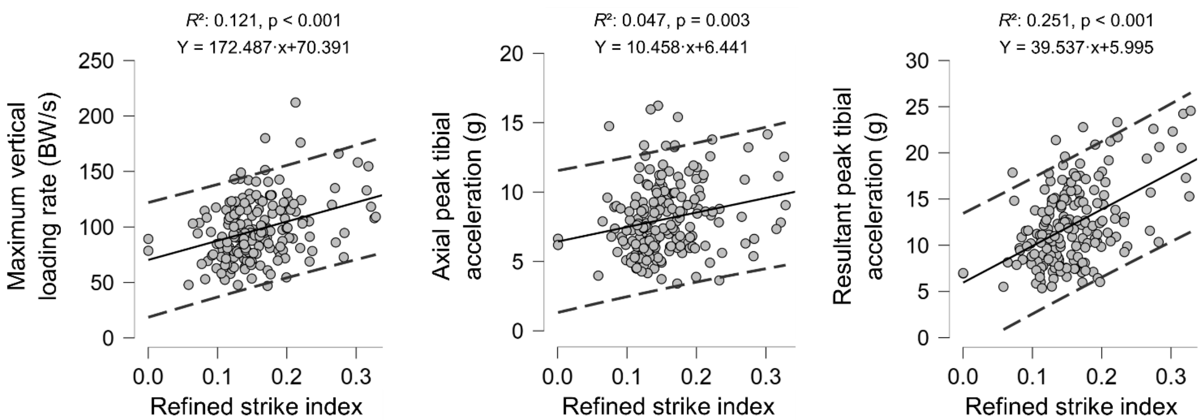


Figure 5. Significant positive linear relationship between the refined strike index and the impact severity. Solid lines indicate that the refined strike index contributed to the magnitude of the peak instantaneous vertical loading rate of the ground reaction force, the axial peak tibial acceleration, and the resultant peak tibial acceleration. Confidence interval boundaries are displayed as green lines with dots. Each dot represents a rearfoot strike in the scatter plots.

Discussion

How the foot unrolls

Our observation that most runners demonstrated a rearfoot strike in self-selected footwear is consistent with previous observations employing a strike index method for shod running in standardized footwear at submaximal running speed (Breine et al., 2014; Cavanagh and Lafortune, 1980). Plantar pressure data captured at high temporal resolution (500 Hz) and spatial resolution (7.62 x 5.08 mm per sensor) enabled the analysis of the COP movement in the initial contact phase from first foot contact to first metatarsal contact. We observed COP paths demonstrating a very fast anterior progression of the COP in self-selected footwear, which resembled those measured in customized athletic footwear (Breine et al., 2017c, 2017b, 2014). These data strengthen the external validity of a phenomenon of COP paths that quickly progress along the lateral region of the rearfoot zone following the first foot contact.

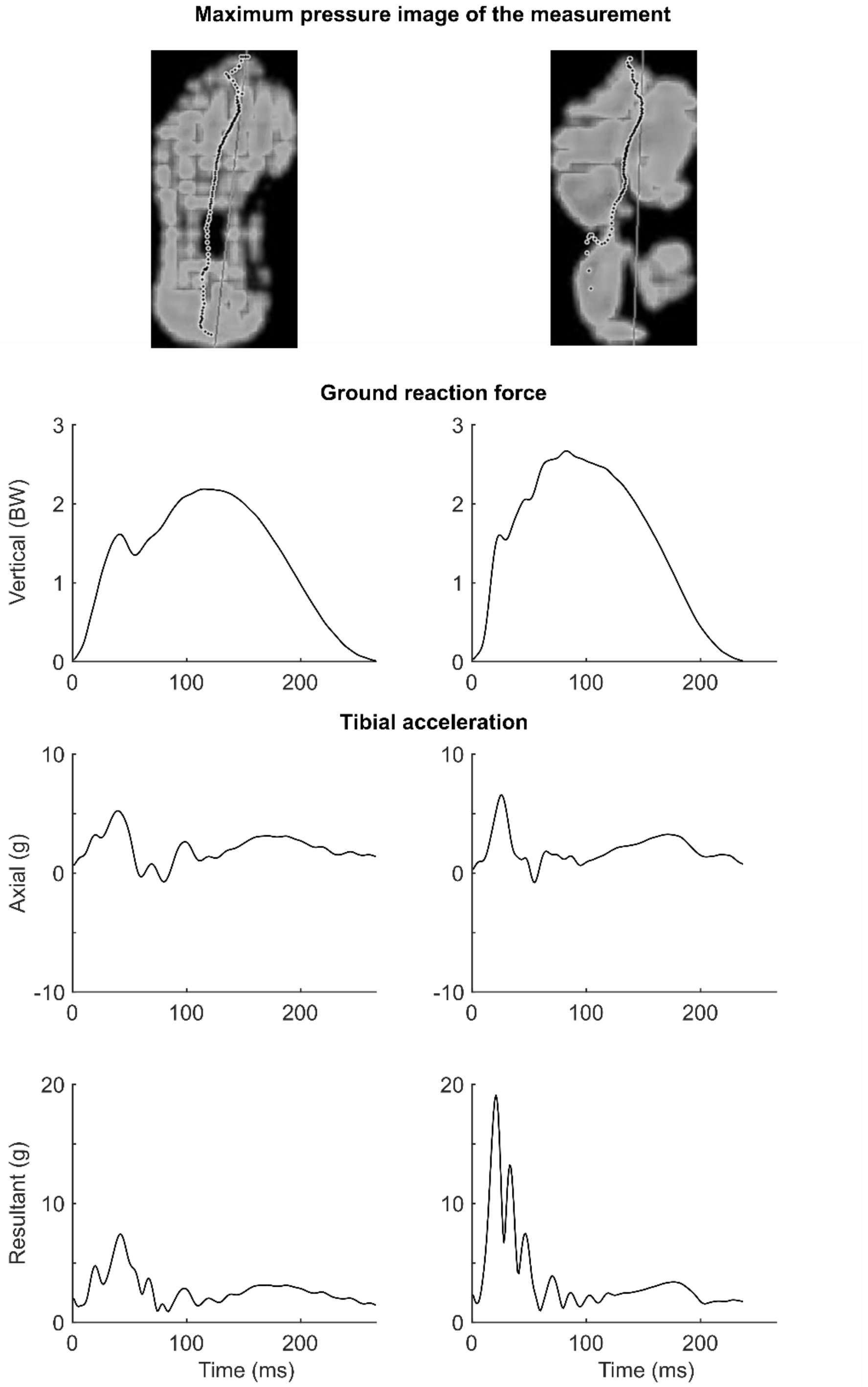
In support of the hypothesis, the COP behavior was dependent on the COP's location at the instant of first foot contact. The more anterior the Y coordinate of the COP at foot strike, the more lateral the X coordinate of the COP was located. This relationship applies to the entire foot strike continuum and is illustrated in Figure 4. On one end of the continuum, the COP at first foot contact is localized in the front one-third of the footprint and near the lateral border of the shoe sole. The COP path of such a forefoot strike has some posterior progression before progressing anteriorly towards the longitudinal foot axis. These observations concur with kinematics studies showing the foot of a forefoot striker lands in plantarflexion and immediately moves into dorsiflexion during the first half of stance (Gruber et al., 2014; Stackhouse et al., 2004). Others also reported greater ankle inversion at foot strike and consequently greater eversion excursion in mid-and forefoot strikes compared with rearfoot strikes (Breine et al., 2017c; Stackhouse et al., 2004), perhaps caused by the more laterally oriented COP at first foot contact. On the other end of the continuum, the foot unroll of pronounced rearfoot strikes starts close to both the longitudinal foot axis and the back edge of the heel, and the COP moves rather slowly towards the midfoot zone (Figure 4). Of particular interest is the first foot contact of less pronounced or subtle rearfoot strikes that occur more laterally in the rearfoot zone and closer to the midfoot zone, and therefore, can reach the metatarsals in a very short period. The interrelation between spatial (i.e., COPy at first foot contact) and temporal (i.e., time of first metatarsal contact) variables of the COP reveals an underlying mechanism of the foot unroll during shod heel-toe running. Therefore, when subcategorizing rearfoot strikes with and without a quick first metatarsal contact, it is logical that kinematic differences were observed at first foot contact (e.g., foot strike angle, foot inversion at initial contact) and later in stance (e.g., range of motion for initial ankle plantar flexion, contact time) (Breine et al., 2017c).

Rearfoot contacts x impact severity

As expected, first foot contacts located near the heel had a slower roll-over in the rearfoot zone and were associated with a less severe impact. The correlation between subtle rearfoot strikes and a greater vertical loading rate is in agreement with our previous study (Breine et al., 2017c), with the main difference being the choice of footwear. The magnitude of the axial and resultant peak tibial accelerations also depended on the refined strike index. The body utilizes different mechanisms to cope with the impact imposed from striking the ground. Shock can be attenuated by active (e.g., eccentric muscular contraction) and passive (e.g., heel fat pad) mechanisms. For instance, adding muscles to a musculo-skeletal and ground reaction force model reduced the maximal vertical loading rate substantially when compared to an equivalent system with no muscles (Gerritsen et al., 1995). Gerritsen et al. (1995) argued that a flatter foot angle at touchdown (i.e., a greater strike index) leads to less eccentric muscular contraction of the ankle-dorsiflexion muscles, making less energy absorption possible, causing the impact force to be higher during heel-toe running (Gerritsen et al., 1995). Most of the energy, however, was absorbed by the viscoelastic surface model that combined the heel-pad, shoe and ground (Gerritsen et al., 1995). The heel pad and shoe can attenuate part of the impact the body experiences during running on a given surface (De Clercq et al., 1994; Shorten and Mientjes, 2011). The quick progression of the COP to the midfoot zone in some of the rearfoot strikes may hamper the full utilization of the cushioning foreseen in conventional athletic footwear. The results of this study may have implications for footwear design. Foot contacts showing a quick COP progression along the lateral border of the rearfoot region would benefit mainly from cushioning in the midfoot zone for impact reduction (Breine et al., 2017b).

Variability in the peak tibial accelerations was most marked for the axial component. The rather wide confidence interval in figure 5 suggests the axial peak tibial acceleration is a poor predictor of the foot placement in level running. The resultant peak tibial acceleration was more affected by the form of heel-toe running and incorporates the three orthogonal components of acceleration. Based on these results, we hypothesize the foot strike particularly affects tibial acceleration in the horizontal plane during the impact phase of the running gait. Our results were able to explain only 4% to 24% of the variance in the impact characteristics. Uninvestigated variables such as lower extremity stiffness (Shih et al., 2019), static foot posture (Williams et al., 2004), the thigh position at mid-swing (Schmitz et al., 2014), global running mechanics such as contact time (Breine et al., 2017c), and midsole foam material properties (Shorten and Mientjes, 2011) might contribute to the unexplained variance in impact severity.

The idea of pronounced rearfoot striking inducing the greatest impact severity during shod running is to be rejected, even in regular athletic footwear. It tackles a long-standing paradigm that sometimes persists because of convenience and habit despite the presence of compelling evidence (Breine et al., 2017c; Stiffler-Joachim et al., 2019; Van den Berghe et al., 2021a). For example, Futrell et al. (2018) postulated rather recently that harder landings have greater loading rates and are accompanied by a visible impact peak in the vertical component of the ground reaction force curve. Contrary to this postulate, our data suggest that visible impact peaks generally have smaller vertical loading rates than vague or visually blunted impact peaks in heel-toe running. Visible impact peaks are considered to be a characteristic of pronounced rearfoot strikes at the back edge of the heel. Contrarily, we noted vague to visually blunted impact peaks in rearfoot strikes having a rather high refined strike index of which the COP demonstrated a very quick foot unroll in the initial contact phase (Figure 6). This makes sense because these less pronounced rearfoot strikes are more closely situated to a midfoot strike on the strike index continuum. The mean curve of the vertical ground reaction force in the midfoot strikes has shown a characteristic absence of the impact transient (Breine et al., 2017b; Cavanagh and Lafortune, 1980). Consequently, a visual inspection of the curve of the vertical ground reaction force is insufficient to identify a subtle rearfoot strike as the rearfoot strike it is.



Refined strike index	0.108	0.315
Time of first metatarsal contact (%)	13.5	1.7
Maximum instantaneous vertical loading rate (BW/s)	56.78	132.98
Axial peak tibial acceleration (g)	5.12	7.34
Resultant peak tibial acceleration (g)	7.49	20.55

Figure 6. Exemplar time series of the vertical ground reaction force, axial tibial acceleration, and resultant peak tibial acceleration during stance (ms). The trials of the two subjects were situated at the opposite ends of the rearfoot strike spectrum. The black points shown on the footprint are separated in time by 2 ms and thus their distance apart on the shoe outline indicates the rate of change of position of the center of pressure.

Footstrike identification in distance running

If proper identification of footstrike is the aim, we advise collecting high-speed plantar pressure data for calculation of the refined strike index. Otherwise, if the classic strike index is calculated from raw force plate data (Williams and Cavanagh, 1987), rearfoot strikes can be misidentified as a midfoot strike. For example, the classic strike index would categorize the rearfoot strike of the exemplar trial in figure 3 as a non-rearfoot strike. The pressure measurements allowed direct localization of the COP on the plantar footprint and at small vertical ground reaction. The median value of 25 N at first foot contact was less than the threshold value of 50 N or more in vertical ground reaction force that previous studies employed to define the instant of foot strike (Cavanagh and Lafortune, 1980; Stiffler-Joachim et al., 2019). Two-dimensional video can suffer from perspective error and often has an inferior data capturing rate compared to the 2-m Footscan system, which makes it challenging to identify a subtle rearfoot strike properly. Next to methods on basis of quantitative data, the runners had difficulty self-identifying their foot contact "type". This result is consistent with the data of Shorten & Pisciotta (2017), who found it safe to assume that the self-diagnosed foot contact type is unrelated to the actual foot contact. Discrepant results in published literature can simply be artifacts from researchers employing different methods of foot strike identification.

Limitations

Our results are specific to running in an unfatigued state and at a single test speed. The phenomenon of a fast progression of the COP path following a first foot contact in the rearfoot zone has been observed at multiple running speeds in standardized footwear (Breine et al., 2014). Therefore, this phenomenon is probably also present in self-selected footwear at multiple running speeds. The relative time from the first foot contact to the first metatarsal contact did not change substantially following a fatiguing long-distance run (Willems et al., 2012). Therefore, this phenomenon is probably also present in fatiguing runs.

The first left and right foot contacts were selected for foot contact analysis. This selection process has been a realistic scenario to study foot strikes in large groups of runners (Larson et al., 2011; Shorten and Pisciotta, 2017). The impact magnitudes were, however, averaged over five contacts per foot side. Synchronously collected and processed data might improve the evaluation of any relationships between impact severity and the COP movement. The variety in footwear might confound the relationship between impact severity and the analyzed variables. The objective of utilizing standardized footwear is ostensibly to remove a source of variance between subjects (Hunter et al., 2020). A significant Pearson correlation coefficient between the refined strike index and the instantaneous vertical loading rate during heel-toe running was found in the dataset of Breine et al. (r = 0.651, p < 0.001, 95% CI = [0.432, 0.797]), standardized running footwear) and in the dataset of the present study (r = 0.348, p < 0.001, 95% CI = [0.216,0.467], self-selected running footwear). Although the refined strike index achieved a greater range of rearfoot strikes in the present study (0.042 to 0.329, minimum to maximum) than in our previous study (0.039 to 0.232), the value of the correlation coefficient suggests that differences in footwear may influence the strength of the relationship.

Future research

We propose two separate areas of future research. First, future research should determine the intra-individual changes in foot contact that occur with real-time biofeedback on musculoskeletal loads in level running. Based on our research findings, a shift towards a more pronounced rearfoot strike that is accompanied by a slower roll-over in the initial contact phase could induce a decrease in impact severity. The more pronounced rearfoot strikes might have less axial and resultant peak tibial accelerations during level running, but it remains to be seen whether structure-specific loading (e.g., tibial bending moment) and loading further up the leg (e.g., eccentric knee work) would be affected by the footstrike during heel-toe running. Second, our findings do not necessarily indicate that running with a quick progression of the COP along the lateral region of the rearfoot zone is hazardous for developing an injury. Prospective epidemiological studies providing insight into the risk of injury would be useful to that end.

Conclusion

The current study showed clear relationships in COP behavior in distance running. The relationship between COP coordinates at foot strike was non-linear, with the Y coordinates associated with pronounced rearfoot striking observed among the lowest X coordinates. The COP of these rearfoot strikes also had tendency to stay longer in the rearfoot zone than less pronounced (i.e. subtle) rearfoot strikes. Rearfoot strike was the most prevalent category at ~3.2 m/s in a large group of distance runners wearing self-selected athletic footwear, as previously shown in a shoe-controlled study by our group. We again observed large heterogeneity in COP trajectories affecting the impact severity. In pronounced rearfoot strikes, the first contact near the back edge of the heel was associated with smaller peak tibial accelerations and vertical loading rate.