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TECHNICAL NOTE

Foot strike pattern and impact continuous measurements during a trail running race: proof of concept in a world-class athlete

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Foot strike identification has become an important topic since it may be related to injury risk and performance. Due to step variability and the influence of environmental features on running biomechanics, it is relevant to assess as many steps as possible in field conditions. Our purpose was to apply a novel simple method to assess foot strike and impact from continuous acceleration measurements over a 45 km trail running race. Three wireless tridimensional accelerometers were set on the left tibia and shoe (at the heel and metatarsals) of the current best ultratrail runner. Vertical, antero-posterior and resultant peak tibial accelerations and median frequencies were measured. Step frequency (SF) was calculated from tibial acceleration. Foot strike was quantified from the time between heel and metatarsal peak accelerations (THM). Foot strike classification was performed according to THM criteria and expressed in percentages of rearfoot, midfoot and forefoot steps. Multiple linear regressions were computed to assess relationships between the impact magnitude and slope, SF and THM. Over the first 20 km, 5530 steps were analysed. The pattern classification revealed on average 18.5% of rearfoot strike, 32.6% of midfoot strike and 48.9% of forefoot strike over the ∼82 min analysed in the runner studied. The impact magnitude for him may be related to slope, also taking into account speed, SF and landing technique. The main findings of this study were that (1) portable accelerometers make possible the assessment of foot strike and shock acceleration *in situ*, (2) the antero-posterior and resultant components of tibial acceleration should not be neglected in the measurement of stress severity, and (3) the trail running world champion presents an atypical foot strike profile.

Keywords: accelerometers; running pattern; impact; trail running; entire race

1. Introduction

In recent years there has been growing interest towards the identification of running patterns for clinical, training and industrial purposes. Three landing techniques have been identified: a rearfoot strike (RFS), in which the point of first contact with the ground is the heel or the rear third part of the sole and in which the midfoot and forefoot parts do not contact the ground at foot strike; a forefoot strike (FFS), in which the point of the first contact was the forefoot or the front half of the sole and in which the heel does not contact the ground at foot strike but slowly goes down to touch the ground during midstance; a midfoot strike (MFS), in which the heel and the ball of the foot land quasi-simultaneously, the point of the first contact can be thus either the rearfoot or forefoot parts (Altman & Davis, 2012; Hasegawa, Yamauchi, & Kraemer, 2007). Numerous studies have investigated their effects on joint loading (Kulmala, Avela, Pasanen, & Parkkari, 2013; Rooney & Derrick, 2013), impact (Delgado et al., 2012; Giandolini et al., 2013; Lieberman et al., 2010), tendon strain (Edwards, Steele, Purdam, Cook, & McGhee, 2013), and more generally on running-related injury risk (Daoud et al., 2012). Others have focused on their influence on performance through their potential effects on running economy (Ogueta-Alday, Rodriguez-Marroyo, & Garcia-Lopez, 2013; Perl, Daoud, & Lieberman, 2012). Acute or prolonged effects of footwear on foot strike pattern has also been investigated (Horvais & Samozino, 2013; Ridge et al., 2013; Squadrone & Gallozzi, 2009; Warne & Warrington, 2012) while, from an epidemiological standpoint, other investigations have focused on the classification of foot strike among different populations of runners and different practices (Hasegawa et al., 2007; Hayes & Caplan, 2012; Kasmer, Liu, Roberts, & Valadao, 2013a, 2013b; Kasmer, Wren, & Hoffman, 2013; Larson et al., 2011; Lieberman et al., 2010).

The most common methods used to identify foot strike patterns are: measurement of the foot-to-ground angle at initial contact by video analysis (Hasegawa et al., 2007; Kasmer et al., 2013a, 2013; Larson et al., 2011), and

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assessment of the foot strike index, defined as the position of the centre of pressure at landing relative to the foot length, derived from the vertical ground reaction force signal (Cavanagh & Lafortune, 1980; Lieberman et al., 2010). Although accurate criteria have been proposed for classification of the foot-to-ground angle method (Altman & Davis, 2012) and the foot strike index method (Cavanagh & Lafortune, 1980), these methods present limitations. They can either be used in lab conditions allowing analysis of many steps, or in the field but this time allowing investigators to analyse only one to three steps. However, as clearly shown by field studies investigating running pattern during prolonged exercise, the foot strike pattern may be asymmetric and altered by the onset of fatigue, and thus might be more or less variable (Hasegawa et al., 2007; Kasmer et al., 2013a, 2013; Larson et al., 2011). Therefore, sampling as many steps as possible might allow us to better take into account modifications in the foot strike pattern that might occur as responses to fatigue or external factors.

The growing popularity of outdoor activities, and especially trail and ultratrail running, supports the need for a better understanding of both the determinants of performance, and the health benefits and risks of such activities. Irregular surfaces, variant slopes and long durations, as well as the fatigue induced and speed variations characterise these activities and influence running biomechanics (Clansey, Hanlon, Wallace and Lake, 2012; Hasegawa et al., 2007; Hayes & Caplan, 2012; Kasmer et al., 2013; Larson et al., 2011; Mizrahi, Voloshin, Russek, Verbitsky, & Isakov, 1997; Mizrahi, Verbitsky, & Isakov, 2000; Morin, Tomazin, Edouard, & Millet, 2011; Muller, Siebert, & Blickhan, 2012). Regarding specifically the effect of the fatigue induced by long duration running activities, previous studies came to the same conclusion that runners seem to adopt a 'smoother and safer running style' post exercise, maybe due to a lower tolerance to shocks as a consequence of the high quantity of foot strike experienced (Degache et al., 2013; Millet et al., 2009; Morin, Samozino, & Millet, 2011a; Morin, Tomazin, et al., 2011). It was suggested that runners might use these kinematic adjustments in order to maintain shock magnitude despite muscular fatigue that might decrease the cushion ability (Abt et al., 2011; Clansey et al., 2012; Mizrahi, Verbitsky, Isakov, & Daily, 2000). One of these adjustments seems to be an increase in step frequency (SF) as previously observed (Degache et al., 2013; Millet et al., 2009; Morin, Samozino, et al., 2011; Morin, Tomazin, et al., 2011). It is worth mentioning that SF was shown to be negatively correlated to several impact-related parameters such as vertical tibial peak accelerations (Derrick, Hamill, & Caldwell, 1998), impact frequency peak (Hamill, Derrick, & Holt, 1995) and tibial contact force (Edwards, Taylor, Rudolphi, Gillette, & Derrick, 2009). Kasmer et al. (2013) investigated changes in foot strike patterns identified by video analysis from two to four steps at three level sites during a 161 km ultramarathon. While this study brought interesting findings on foot strike changes over an ultratrail running race in real practice, it did not provide a full description of the probably variable distribution of the running techniques over the entire race. Therefore, we thought of interest to investigate whether or not the onset of fatigue leads to kinematic alterations (specifically, changes in foot strike pattern and SF) during a race, and when.

Considering the limits of current methods attempting to identify foot strike and the need to study running activities in the field, we recently presented a simple field method based on continuous acceleration measurements aimed at describing foot strike (Giandolini et al., 2014). In the present 'proof of concept' study, we applied this new method to analyse the foot strike pattern over a 45 km official trail running race in a world-class runner while measuring three-dimensional tibial shock. Our objectives were (1) to describe running kinematics (i.e. the repartition of foot strike techniques and SF) in one of the best ultratrail runners, (2) to examine how slope, speed and running time (i.e. potential fatigue onset) influence this repartition and (3) to quantify the overall stress severity sustained by a trail runner over a typical race and to investigate the effects of slope, speed and foot strike pattern on impact severity.

2. Methods

The study took place during the Kilian's Classik™ 2013 (Font-Romeu, France), a 45-km official trail running race with a 1627-m positive elevation. The individual studied was the current world leader in trail and ultratrail running (26 years, 56.5 kg, 171 cm). He ended first with a finish time of 4:23:18 hours. Only the first 20 km of the race were considered because the battery of the global positioning system (GPS) unit died at mid-race. Since we aimed at investigating the effects of speed, slope and running time on kinematic and impact variables, there was no interest in analysing the last 20 km acceleration data without synchronised information about the environmental characteristics. The study was approved by the local ethics committee of the University of Saint-Etienne, and complied with the declaration of Helsinki. The subject was orally informed of the full details of the study by the experimenters, after what his oral informed consent was directly obtained at the end of the face-to-face individual interview with the experimenters. No written consent was established since this study was part of a trail running race, with no additional invasive measurements, for which the subject had already given his consent. The ethic committee approved this consent procedure.

2.1. *Materials*

The subject was equipped with a GPS plugged into one of the three tridimensional accelerometers (Hikob Agile Fox, Hikob, Villeurbanne, France) shown on Figure 1A. One was firmly fixed onto his left tibia (Figure 1B) in a

Figure 1. Placement of the three accelerometers. Panel A represents the accelerometers' placement and attachment onto the subject during the race. Panel B illustrates the placement of the tibial accelerometer without the attachment system, for more clarity. Panels C and D show more precisely the placement and attachment of the metatarsal and heel accelerometers, respectively.

customised elastic strap tightened to the limit of the subject's comfort (Shorten & Winslow, 1992). The two others were installed in fitted pockets firmly fixed by elastic straps (Figures 1C and 1D), and set on the left shoe at the heel and onto the dorsal surface of the foot above the metatarsals, contrary to the setting in Giandolini et al. (2014) to better protect it from rocks, water, mud, etc.

2.2. *Measurements and parameters of interest*

Accelerations and GPS data were time-synchronised by a common acquisition system (Hikob, Villeurbanne, France) and sampled at 1300 and 12 Hz, respectively. They were collected on micro-SD (Secure Digital) cards. A single acquisition was performed from the start to the end of the race, obtaining an ~4.5 hours acquisition but as previously mentioned only the first half of the race was analysed. Eleven sections presenting typical slope and speed profiles were extracted from the GPS signal over the first 20 km of the race (Table 1).

Data analysis was performed using Scilab 5.4.1 software (Scilab Enterprises, Orsay, France). Running speed and slope were computed from altitude, latitude and longitude data obtained from the GPS measurement. The resultant acceleration was calculated from vertical (x-axis, corresponding to the tibial longitudinal axis), antero-posterior (y-axis, corresponding to the axis of the tibial anterior medial aspect) and medio-lateral acceleration (z-axis,

Table 1. Characteristics of the eleven sections analysed. They were numbered according to their order of occurrence over the race. Mean ± SD for the slope and the running speed, and the overall duration of analysis and number of analysed steps were calculated.

Section #	Slope (%)	Speed (km·h^{-1})	Duration (min)	Number of steps analysed
1	1.4 ± 5.63	14.2 ± 2.05	9.4	672
2	−6.3 ± 7.12	16.3 ± 1.7	1.7	101
3	6.8 ± 4.8	11.7 ± 1.99	16.7	1102
4	34.7 ± 11.6	4.29 ± 1.44	4.9	251
5	−18.5 ± 6.77	15.8 ± 2.15	5.3	376
6	4.2 ± 1.63	13 ± 1.12	6.4	421
7	1.6 ± 6.82	11.1 ± 1.08	7.5	501
8	14.9 ± 7.04	8.2 ± 1.81	10	702
9	3.8 ± 4.77	11.6 ± 1.29	8.5	602
10	14.6 ± 4.72	6.8 ± 1.07	6.7	451
11	21.1 ± 11.7	6.8 ± 1.49	5	351
	7.11 ± 6.61	10.9 ± 1.56	82.1	5530

corresponding to the axis orthogonal to the *y*-axis in the transversal plane) components. Impact-related parameters were calculated from time and frequency analysis. For the time analysis, vertical, antero-posterior and resultant tibial accelerations were 50 Hz low-pass filtered to limit the resonance frequency of the attachment in the quantification of impact shock magnitude (typically from 60 to 90 Hz according to Shorten & Winslow, 1992). Then, peak tibial accelerations were obtained (PTAx (vertical Peak Tibial Acceleration), PTAy (antero-posterior Peak Tibial Acceleration) and PTAr (resultant Peak Tibial Acceleration)). The frequency along the verical, antero-posterior and resultant tibia axes analysis was performed on stance phases, respectively, in vertical, antero-posterior and resultant dimensions as described by Shorten and Winslow (1992). With the deflection before the vertical peak tibial acceleration as the start of the impact phenomenon, 0.3 s subsamples were extracted from tibial vertical, antero-posterior and resultant acceleration signals. Each subsample was filled with zero values to obtain a total of 512 values. The power spectral density was then calculated using the Fast Fourier Transform for tibia acceleration signals in the vertical (PSDx), antero-posterior (PSDy) and resultant (PSDr) dimensions. PSDs were then interpolated so each frequency bin was 2 Hz. Median frequencies were calculated from each power spectral density (PSD) within the 2–100 Hz range in vertical (MDFx), antero-posterior (MDFy) and resultant (MDFr) dimensions.

SF was calculated from the vertical tibial acceleration signal as the inverse of strides cycle duration (i.e. time between two consecutive tibial peaks) divided by two. The foot strikes were identified from heel and metatarsal acceleration signals 50 Hz low-pass filtered applying the time between heel and metatarsal peak accelerations (THM) method (Giandolini et al., 2014). It is based on the THM considering the heel peak acceleration occurrence as t_0. Foot strikes were then classified into three categories (RFS, MFS and FFS) using the THM-based classification proposed by Giandolini et al. (2014): FFS < −5.49 ms < MFS < 15.2 ms < RFS. For each section, the respective parts of RFS, MFS and FFS were then expressed in percentages of all steps analysed over the section. All complete and valid steps were analysed. Previous measurements in our laboratory showed a 3 ms difference in THM (i.e. time between heel peak acceleration and metatarsals peak acceleration) measurement between the current forefoot placement and the one used during validation of the method (Giandolini et al., 2014), i.e. above the midsole on the external face of the shoe. These three milliseconds were subtracted from each THM measured in the present study to be in line with the criteria of classification proposed in Giandolini et al. (2014). For the forefoot attachment, the elastic strap was inserted between the top midsole and the upper of the shoe during its construction.

2.3. *Statistics*

Means and standard deviations (mean ± SD) were calculated for THM and impact-related parameters within each section. Correlations were tested (Bravais and Pearson tests) between slope, speed, average SF and average foot strike parameters (THM, %RFS, %MFS and %FFS) values of the eleven sections ($n = 11$). Using values of THM and impact-related parameters of all analysed steps and the average slope and SF values of their respective section, multiple linear regressions were computed to test the respective effect of environmental and kinematic parameters supposed a priori to influence shock magnitude (slope, SF and THM as independent variables) on the impact-related parameters (PTAx, PTAy, PTAr, MDFx, MDFy and MDFr as dependent variables). To avoid colinearity, speed was not included as an independent

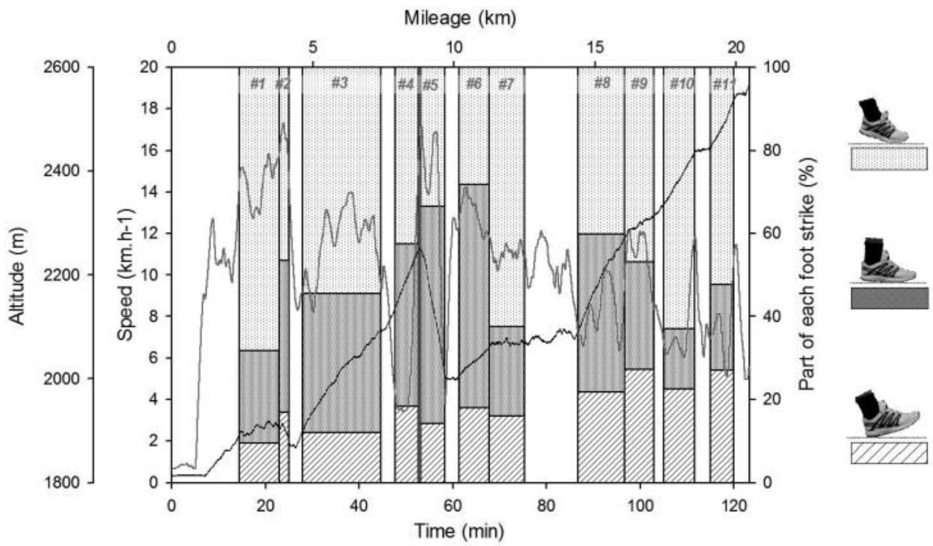

Figure 2. Altitude (black line) and speed (grey line) over the first 20 km of the race. Bar charts represent the repartition of foot strikes (RFS, MFS and FFS) within the eleven analysed sections.

variable because we observed a priori strong correlations between slope and speed ($r = -0.93$, $P < 0.0001$) as well as between SF and speed ($r = 0.80$, $P < 0.001$). The level of significance was set at $P < 0.05$.

3. Results

The race topography over the first 20 km is represented in Figure 2 along with the analysed sections. The average speed over the eleven sections was 10.9 ± 1.6 km·h^{-1} (Table 1). A total of 5530 steps was considered for analysis, corresponding to a cumulate duration of ~82 min. On average, 503 ± 267 steps were analysed per section, which is equivalent to 7.46 ± 3.86 min per section (Table 1).

Kinematic results are reported in Table 2. The subject showed an average foot strike repartition of ~18% of RFS, ~33% of MFS and ~49% of FFS. His average THM was −1.28 ± 15.9 ms. As expected, there was a significant correlation between slope and speed ($r = -0.93$, $P < 0.0001$). SF was significantly correlated to both slope and speed ($r = -0.86$ and $r = 0.80$, respectively, $P < 0.001$). None of the foot strike parameters (THM, %RFS, %MFS and %FFS) was related to slope, speed or SF. Moreover, a significant correlation was found between %RFS within each section and the position of sections in the race ($r = 0.88$, $P < 0.001$).

Impact-related parameters are reported in Tables 3 and 4. Statistical results are reported in Table 5. Since speed was strongly correlated to slope, only slope was included in the multiple regression analysis as an environmental independent variable. Hence the following results regarding the effect of slope also account albeit indirectly, for speed. The

Table 2. Mean ± SD for kinematics and foot strike parameters within the eleven sections including step frequency (SF), time between heel and metatarsal peak accelerations (THM) and percentages of each foot strike pattern (%RFS, %MFS, %FFS).

Sections #	SF (Hz)	THM (ms)	%RFS	%MFS	%FFS
1	3.05 ± 0.21	−5.07 ± 14.6	16.6%	12.9%	70.5%
2	3.01 ± 0.26	3.61 ± 14.1	24.4%	49.3%	26.4%
3	2.91 ± 0.13	0.31 ± 17.5	29.1%	22.3%	48.6%
4	1.72 ± 0.12	−2.30 ± 18.8	22.4%	23.7%	53.9%
5	3.17 ± 0.34	1.15 ± 15.2	19.4%	33.3%	47.3%
6	3.01 ± 0.11	7.13 ± 13.1	27.3%	45.9%	26.8%
7	2.92 ± 0.20	−3.99 ± 16.4	17.9%	15.1%	67.0%
8	2.78 ± 0.16	1.05 ± 17.9	26.0%	26.3%	47.7%
9	2.84 ± 0.16	2.40 ± 16.7	27.9%	22.3%	49.8%
10	2.73 ± 0.26	−2.69 ± 17.8	21.4%	16.8%	61.8%
11	2.72 ± 0.22	3.73 ± 17.1	28.6%	28.2%	43.1%
	2.81 ± 0.37	0.48 ± 16.3	23.7 ± 4.48%	26.9 ± 11.8%	49.4 ± 14.2%

Table 3. Mean ± SD for impact-related parameters in the time domain within the eleven sections including vertical, antero-posterior and resultant peak tibial accelerations (PTAx, PTAy and PTAr).

Sections #	PTAx (g)	PTAy (g)	PTAr (g)
1	11.2 ± 5.56	8.37 ± 4.52	15 ± 5.63
2	19.0 ± 4.94	13.0 ± 4.78	22.3 ± 3.71
3	6.25 ± 2.74	3.85 ± 1.81	8.63 ± 3.07
4	4.49 ± 2.56	1.29 ± 0.92	4.75 ± 2.50
5	17.1 ± 4.80	9.36 ± 4.37	20.6 ± 5.38
6	6.56 ± 1.74	5.54 ± 2.20	9.78 ± 2.16
7	8.29 ± 4.26	5.00 ± 2.68	10.1 ± 4.13
8	4.79 ± 2.84	2.82 ± 1.83	5.78 ± 3.13
9	6.63 ± 3.62	3.60 ± 2.27	7.79 ± 3.86
10	3.73 ± 1.71	2.02 ± 0.92	4.22 ± 1.79
11	4.43 ± 2.25	2.36 ± 1.29	4.88 ± 2.27
	8.41 ± 3.37	5.20 ± 2.51	10.4 ± 3.42

Table 4. Mean ± SD for impact-related parameters in the frequency domain within the eleven sections including vertical, antero-posterior and resultant median frequencies (MDFx, MDFy and MDFr).

Sections #	MDFx (Hz)	MDFy (Hz)	MDFr (Hz)
1	21.5 ± 5.79	30.5 ± 8.54	15.1 ± 4.49
2	23.5 ± 7.61	32.4 ± 8.74	14.3 ± 3.86
3	18.9 ± 5.55	24.6 ± 9.66	15 ± 5.94
4	19.4 ± 9.78	17.6 ± 12.1	17.5 ± 10.7
5	24.3 ± 5.49	26.5 ± 7.9	14.3 ± 5.95
6	18.9 ± 5.16	25.5 ± 6.8	12.4 ± 4.25
7	19.5 ± 5.37	23 ± 7.43	13.9 ± 5.32
8	17.4 ± 6.57	18.8 ± 7.06	15.7 ± 5.82
9	18.8 ± 5.99	20.3 ± 7.31	14.7 ± 5.7
10	15 ± 6.58	15.9 ± 6.67	14.3 ± 5.99
11	16.5 ± 6.41	17.1 ± 6.96	15.3 ± 6.36
	19.4 ± 2.81	22.9 ± 5.53	14.9 ± 1.25

multiple regression analysis showed that impact-related parameters were negatively related to slope in vertical and antero-posterior directions. SF was negatively related to PTAx, MDFx, PTAr and MDFr. However, it was positively related to MDFy and not correlated to PTAy. Concerning the influence of THM on impact magnitude, whereas a negative relationship was found between PTAx and THM, PTAy was positively related to THM. Further, THM was positively related to MDFx, MDFy and MDFr.

4. Discussion

The purpose of this study was to apply a simple new method aiming at assessing the foot strike repartition and impact-related parameters during an entire trail running race in a world-class individual. It shows the possible improvement of our scientific understanding of this outdoor activity *in situ* by taking into consideration inter-step variability and environmental constraints. This method requires two wireless accelerometers at the heel and metatarsals for the pattern identification by the THM measurement (Giandolini et al., 2014), plus appropriate signal recording and stocking tools as tight attachments. Foot strike repartition can be then calculated over the recorded sections. A tridimensional accelerometer at the tibia further permits measurement of shock magnitude in the vertical, antero-posterior and resultant directions. The main benefit of this method is its user-friendliness during setting up and analysis. A possible limitation could be indistinctness of signals due to an insufficient system of attachment, but it proved to be of good quality, as shown in Figure 3, and the ranges of values of impact-related parameters were consistent with previous studies using accelerometers fixed externally relative to the speed or slope conditions as shown in Figure 4 (Mercer, Vance, Hreljac, & Hamill, 2002; Mizrahi, Verbitsky, & Isakov, 2000; Valiant,1989).

When one aims at describing foot strike, there are two main advantages of using this acceleration-based method: the number of steps analysed, and the possibility of *in situ* analysis. Indeed, the present results were based on about 5500 steps over approximately 20 km of a real race,

Table 5. Regression models with their R^2 and P values for the constant and independent variables. The weighted β values were also reported for independent variables. Dependent variables are PTAx, PTAy, PTAr, MDFx, MDFy and MDFr. Independent variables are slope, SF and THM.

		Constant		Slope			SF			THM		
	R^2	Coefficient	P	Coefficient	P	β	Coefficient	P	β	Coefficient	P	β
PTAx	0.424	271	<0.001	−4.07	<0.001	−0.874	−58.6	<0.001	−0.299	−0.144	<0.001	−0.048
PTAy	0.325	57.5	<0.001	−1.90	<0.001	−0.563	0.972	0.766	0.007	0.069	0.014	0.032
PTAr	0.485	252	<0.001	−4.61	<0.001	−0.845	−43.5	<0.001	−0.190	0.054	0.177	0.015
MDFx	0.102	37.7	<0.001	−0.285	<0.001	−0.471	−5.84	<0.001	−0.230	0.035	<0.001	0.089
MDFy	0.144	16.4	<0.001	−0.242	<0.001	−0.283	2.80	0.003	0.078	0.079	<0.001	0.144
MDFr	0.015	20.9	<0.001	0.014	0.357	0.026	−2.17	<0.001	−0.095	0.014	0.008	0.041

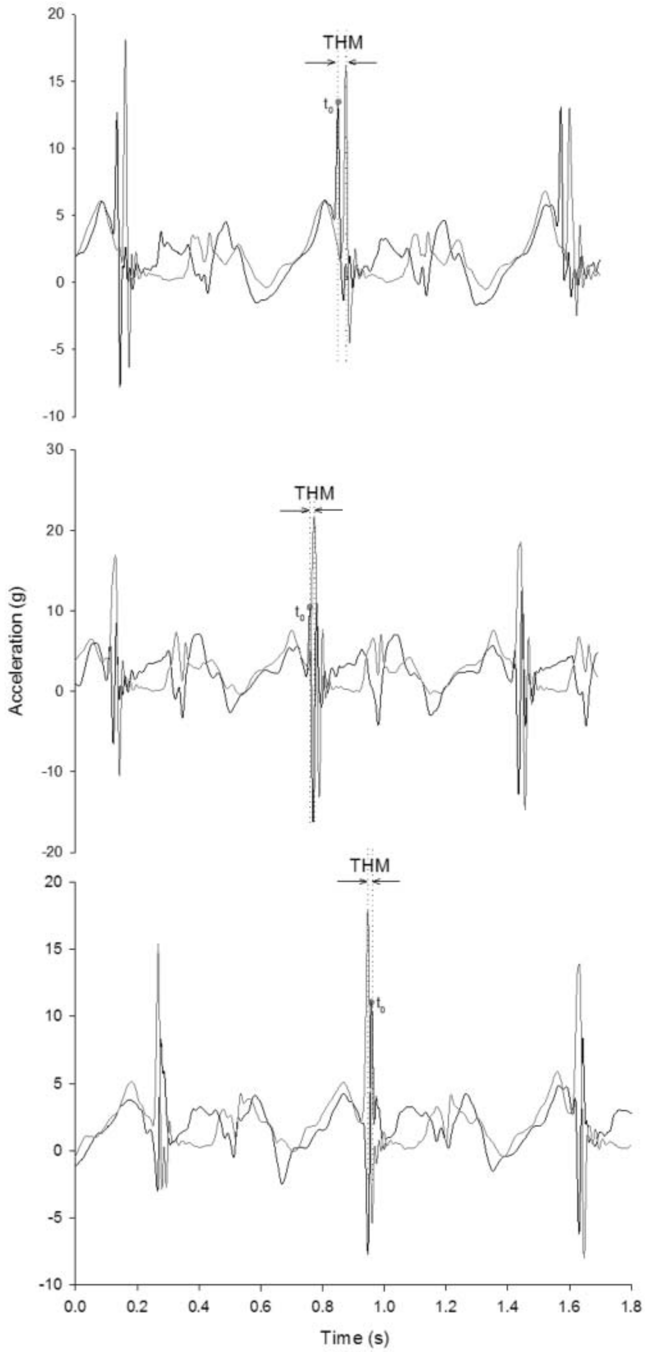

Figure 3. Typical heel (black line) and metatarsal (grey line) acceleration signals. Panel A represents three consecutive RFS steps within the ninth section (THM for the second step represented was 26.2 ms), panel B represents three consecutive MFS steps within the second section (THM for the second step represented was 7.69 ms), and panel C represents three consecutive FFS steps within the third section (THM for the second step represented was −12.3 ms).

including variable slopes, speeds and terrain. This allows step variability to be taken into account and assessment of the running pattern, and impact, over a continuous period rather than only once at a given point in the race, which may not be representative of the overall run. In activities such as trail running, characterised by irregular surfaces, various slopes and speeds, or fatigue onset, runners are led to adapt and change their running patterns. This field approach might allow researchers, clinicians and industrials to investigate the individual use of foot strike patterns in different conditions, the associated impact severity and its sensibility to fatigue. For example, the present case study demonstrated that the subject, a world-class trail runner, was predominantly a forefoot striker over the 20 km

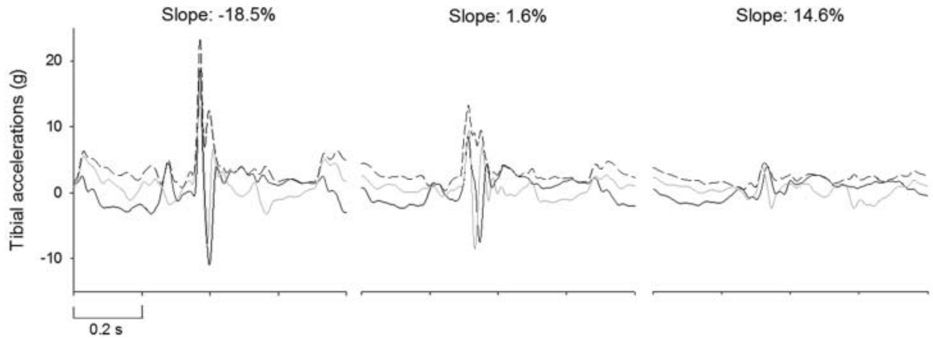

Figure 4. Typical signals of tibial accelerations for the vertical component (black line), antero-posterior component (grey line) and resultant component (dashed line) in various conditions of slope.

recorded and that only 18.5% ± 5.72% of his steps were RFS, borne out by the subjects own feelings regarding his running foot strike. This is very atypical for an extreme distance runner. In comparison, Hasegawa et al. (2007), Larson et al. (2011) and Kasmer et al. (2013a) reported rates of RFS runners over marathons from 74.9% to 93.7%, which is quite similar in a 50 km trail running race (85.1%) or a 161 km ultramarathon (ranging from 79.9% to 89%) as observed by Kasmer and his teams (Kasmer et al., 2013b, 2013). Further, the proportion of RFS increased over the 20 km. Since this result is quite difficult to interpret because of variable slopes, surfaces and speeds between the sections considered, this increase in the rate of RFS steps could be a result of the predominantly ascendant profile of this 20-km portion (approximately 1054 m of positive elevation), in particular over the last four sections during which the slope increased considerably. Given that both uphill running (Sloniger et al., 1997) and FFS running (Giandolini et al., 2013; Shih, Lin, & Shiang, 2013) increase the activation of plantar flexors, the subject may have modified his global foot strike repartition as a strategy to relax these muscles and/or walk which would increase the number of RFS steps. Note that this race was not a major challenge for the runner studied.

In addition, this study aimed to quantify the overall stress severity sustained by a trail runner and to better understand the external factors influencing it. Impact-related parameters were negatively related with slope: the lower slope and thus the higher the speed, the higher the tibial peak accelerations and the median frequencies in both vertical and antero-posterior directions. Previous studies have outlined this relationship between vertical peak and slope (Hamill, Clark, Frederick, Goodyear, & Howley, 1984; Lafortune, 1991; Mizrahi, Verbitsky, & Isakov, 2000). Contrastingly, Mizrahi, Verbitsky, and Isakov (2000) observed no change in vertical median frequency between level and −4° downhill running, although this slope may have been too close to level running to observe any change. In the Mizrahi et al. study (Mizrahi, Verbitsky, & Isakov, 2000) the speed was the same in level and downhill running bouts whereas in the present study speed increased as slope decreased. It should also be noted that the various surfaces (e.g. stones, mud, etc.) were not identified in this study but it would be of great interest to take them into account in the analysis. It is also worth mentioning that the weighed β values for slope were rather higher than for SF and THM (Table 5). It suggests that the severity of impact is more sensitive to the slope than to the SF or foot strike pattern, although the effect of these three variables is significant.

Significant negative correlations were observed in the multiple regression analysis between SF and vertical and resultant peak accelerations as well as vertical and resultant median frequencies. However, a positive correlation was found between SF and antero-posterior peak acceleration. This tends to support the fact that SF influenced the impact-related parameters independently from slope and foot strike pattern. An increase in SF would result in lower vertical and resultant peaks as well as lower vertical and resultant median frequencies, but higher antero-posterior peak acceleration at the tibia without changing antero-posterior median frequency. To our knowledge, no study has hitherto investigated the effect of stride frequency on antero-posterior peak acceleration or median frequency at tibia. Nevertheless, previous investigations have observed, at a set speed, that increasing SF or decreasing step length resulted in lower vertical tibial peak accelerations (Derrick et al., 1998), lower impact frequency peak (Hamill et al., 1995) and lower tibial contact force (Edwards et al., 2009). Although our findings are in line with these observations, they are not consistent with those of Mercer et al. who observed no relationship between SF and vertical leg peak acceleration (Mercer et al., 2002). One possible explanation for this divergence could be that in the study of Mercer et al. running speed varied, and indirectly, so did SF. The peak leg acceleration measurements might thus reflect the opposite effects of speed and SF. Otherwise, further investigations are needed to clarify and confirm the relationship between SF and antero-posterior impact magnitude.

The multiple regression analysis also showed that THM was positively correlated to antero-posterior and resultant peak accelerations and to vertical, antero-posterior and resultant median frequencies. Otherwise, it was negatively correlated to vertical peak acceleration. Basically, a more anterior running pattern (i.e. a lower THM) seems to induce a lower peak magnitude in the antero-posterior direction, but a higher one in the vertical direction. Note that the resultant peak acceleration tended to be positively related to THM although not significantly ($P = 0.063$). The tibial acceleration profile contains a low frequency component (4–8 Hz) associated with voluntary leg motion (e.g. stride length, segments alignment and velocity) and the acceleration of the body centre of mass, and a high frequency component (10–20 Hz) representing the rapid deceleration of the lower extremity at initial contact (Gruber, Boyer, Derrick, & Hamill, 2014; Shorten & Winslow, 1992). Variations in tibial peak magnitude may therefore be attributed to changes either in active content, passive content or both. Conversely to a FFS, a RFS is typically characterised by a more extended knee at landing and a lower stride frequency inducing less vertical alignment of the tibia at initial contact (Ahn, Brayton, Bathia, & Martin, 2014; Cavagna & Kaneko, 1977; De Wit, De Clercq, & Aerts, 2000; Shih et al., 2013; Squadrone & Gallozzi, 2009). Based on these previous kinematic results, we can hypothesise that these differences in leg orientation and placement at initial contact may alter the repartition of shock acceleration along the vertical and antero-posterior axis especially in its low frequency component. Adopting a more anterior running pattern may lead to a more vertical segment position at foot strike and thus a higher component of acceleration measured along the vertical axis. Conversely, adopting a heel strike may result in a tilted tibia at landing which may increase the component of acceleration along the antero-posterior axis. Regarding frequency analysis, Gruber et al. (2014) observed from tibial vertical acceleration a lower power of high frequencies when adopting a FFS. The positive relationships observed between THM and median frequencies tend to agree with this finding: a more anterior foot strike would decrease the amplitude of high frequency components of tibial acceleration in vertical, antero-posterior and resultant directions. This lowering of high frequencies at the tibia may be attributed to different damping mechanisms. Running with a FFS induces a higher pre-activation of *gastrocnemii* (Giandolini et al., 2013) potentially attenuating shock frequencies above 40 Hz (Boyer & Nigg, 2007). Greater ankle compliance in forefoot strikers (Lieberman et al., 2010) could also contribute to minimising the intensity of foot-ground collision. While the present data do not allow us to properly discuss the influence of segment motion on peak accelerations, conclusions about the influence of foot strike patterns on tibial shock magnitude are at the present time inconsistent (Delgado et al., 2012; Gruber et al., 2014; Laughton, McClay Davis, & Hamill, 2003; Oakley & Pratt, 1988) and need more investigations.

Finally, the present results highlight the fact that the antero-posterior peak acceleration was almost as intense as the vertical peak acceleration. Among all the studies using accelerometers to investigate impact in running over the last two decades, to our knowledge only Lafortune (1991) chose to assess the magnitude of antero-posterior acceleration; all the others focused only on the vertical component. Lafortune and his collaborators strongly recommended measuring both the vertical and horizontal components to quantify the magnitude of the shock experienced by the lower limb during running and this study clearly adds weight to his recommendation. Although foot strike may not influence the overall severity of the impact, it may change the predominance of the vertical or antero-posterior impact component.

5. Conclusion

This innovative acceleration-based method aims to describe running patterns and measure impact magnitude through continuous recordings. Its main advantages are: a high quantity of analysed steps, a feasible *in situ* investigation, and accessible utilisation and analysis. Keeping in mind that these results only concern the world-class runner studied, we observed over 20 km of a trail running race that (1) only 18% of the about 5500 steps analysed were RFS which is really untypical for an ultra-endurance runner, (2) that the overall stress severity sustained over a trail running race may be influenced by slope – including also speed, step frequency and running pattern, (3) that the antero-posterior acceleration should no longer be neglected when measuring impact magnitude in running. This novel approach may allow researchers to improve their understanding of outdoor running activities as well as risk behaviours, and help industrials to better design shoes for a specific activity and or even for an individual runner.

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