Technical Note

Institution of MECHANICAL ENGINEERS

Journal of SPORTS ENGINEERING AND TECHNOLOGY

Proc IMechE Part P:
J Sports Engineering and Technology
1–6

DOI: 10.1177/1754337117751730
journals.sagepub.com/home/pip
SAGE

Sensor insole for measuring temporal variables and vertical force during sprinting

Ryu Nagahara[1] and Jean-Benoit Morin[2]

Abstract

Temporal variables and vertical ground reaction force have been used as measures characterizing sprinting. A recently developed wireless pressure sensor insole (sensor insole) could be useful for monitoring sprinting in terms of temporal variables and vertical ground reaction force during training sessions. The purpose of this study was to examine the concurrent validity of the sensor insole for measuring temporal and vertical force variables during sprinting. One athlete performed five 50-m sprints, and the step-to-step vertical ground reaction force and plantar pressure were simultaneously measured by a long-force platform system (reference device) and the sensor insole, respectively. The temporal and vertical ground reaction force variables were calculated using signals from both devices, and a comparison was made between values obtained with both devices for 125 steps analyzed. The percentage bias, 95% limits of agreement, and Bland–Altman plots showed low agreement with the reference device for all variables except for step frequency. For the vertical ground reaction force variables, the sensor insole underestimated the values (−18.9 to −48.3%) compared to the force platform. While support time and time to maximal vertical force from the foot strike were overestimated by the sensor insole (54.6 ± 8.0% and 94.2 ± 23.2%), flight time was underestimated (−48.2 ± 15.0%). Moreover, t-test revealed the significant difference in all variables between the sensor insole and force platform, except for step frequency. The bias for step frequency (0.4 ± 7.5%) was small. However, there was heteroscedasticity for all variables. The results from this study demonstrate that a wireless pressure sensor insole is generally not valid to measure the temporal and vertical force variables during sprinting. Thus, using the examined sensor insole for monitoring sprinting characteristics is not recommended at this time.

Keywords

Step frequency, contact time, sprinting, wireless pressure sensor insole, acceleration

Date received: 10 August 2017; accepted: 29 November 2017

Introduction

Temporal variables and vertical ground reaction force (GRF) have been used as measures characterizing maximal-effort sprint running (sprinting), where short support time (ST) and large mean vertical GRF (Fmean) are determinants of high maximal sprinting speed.[1,2] During sprinting, these variables were measured using a force platform (FP).[3,4] However, data can only be collected for one or two steps from one FP. Therefore, recording the data during sprinting for a long distance (over 100 m) by FP is a technical challenge.

As an alternative to FP, a fully wireless pressure sensor insole (sensor insole) has recently been developed for measuring temporal variables and plantar pressures.[5–7] The sensor insole is commercially available and records plantar pressure, which can be considered as an indirect estimate of vertical GRF, during the support phase of locomotion by embedded pressure sensors. Previous studies demonstrated that for GRF variables, the validity and reliability of the sensor insole during walking were relatively high when compared to data from FP, while those from sensor insoles during running and jumping were relatively low.[5–7] For the temporal variables, however, the sensor insole was

[1]National Institute of Fitness and Sports in Kanoya, Kanoya, Japan
[2]Laboratoire Motricité Humaine Expertise Sport Santé (LAMHESS), Université Côte d'Azur, Nice, France

Corresponding author:
Ryu Nagahara, National Institute of Fitness and Sports in Kanoya, 1 Shiromizu-cho, Kanoya 891-2393, Kagoshima, Japan.
Email: nagahara@nifs-k.ac.jp

validated during walking, running and jumping.[5–7] Although this sensor insole could be useful for monitoring sprinting in terms of temporal variables and vertical GRF during a training session, its concurrent validity for such a purpose has never been examined. The characteristics of temporal variables and vertical force between running and sprinting are substantially different. The ST, step frequency (SF), maximal vertical GRF (Fmax) and effective vertical impulse during slow speed running are substantially longer, lower, smaller and smaller than those during sprinting, respectively.[2,8] Thus, the need exists to investigate the validity of the sensor insole for measuring temporal variables and vertical force during sprinting. In a previous study using a custom-built sensor insole (not fully wireless) for detecting the foot strike and toe-off instants,[9] ST was accurately measured during a 60-m sprint. Therefore, this study hypothesized that the sensor insole would be valid, at least in the collection of spatiotemporal variables.

The purpose of this study was to examine the concurrent validity of using wireless pressure sensor insoles for measuring temporal and vertical force variables during sprinting. Such a study may provide useful information for sprinters and coaches who intend to use this device for monitoring characteristics of sprinting during daily training.

Methods

Participant

One male athlete participated in this study (age, 27 years; stature, 1.804 m; body mass, 77.8 kg; personal best record of 100-m race, 11.48 s). Because the purpose of this study was the comparison of temporal and GRF variables during sprinting obtained from two devices, many participants were not necessary. A similar method with a low number of participants and a sufficient number of steps/conditions has been used in previous studies in which the computations were based on comparisons that were independent of participant's characteristics.[10,11] The participant gave written informed consent before participating in this study. This study was approved by the Ethics Committee of the National Institute of Fitness and Sports in Kanoya, Japan, and conducted in accordance with the Declaration of Helsinki II.

Experiment

After a warm-up, the participant performed five 50-m maximal-effort sprints from starting blocks with a 10 min rest interval between sprints. Sensor insoles (OpenGo; Moticon GmbH, Munchen, Germany; 50 Hz) inserted in the left and right spiked shoes and a long FP system consisted of 50 single FPs (TF-90100; Tec Gihan, Uji, Japan; 0.9 × 1.0 m; 1000 Hz) were used to simultaneously measure the plantar pressure and vertical force during the support phase in sprint acceleration for a length of 50 m (Figure 1). The participant wore thin socks and felt comfortable with the well-fitted insoles. The left and right sensor insoles were automatically synchronized before each trial, and the sensor insoles were calibrated using operating software. The sensor insole is fully wireless and has 13 capacitive pressure sensors, as detailed in previous studies.[5–7] Although the sensor insole with half of the capacitive pressure sensors could record plantar pressure at 100 Hz, the highest sampling frequency of the sensor insole that could collect data from all the capacitive pressure sensors was 50 Hz. Accordingly, plantar pressure was recorded using the sensor insole at 50 Hz to collect data from the 13 sensors in each insole.

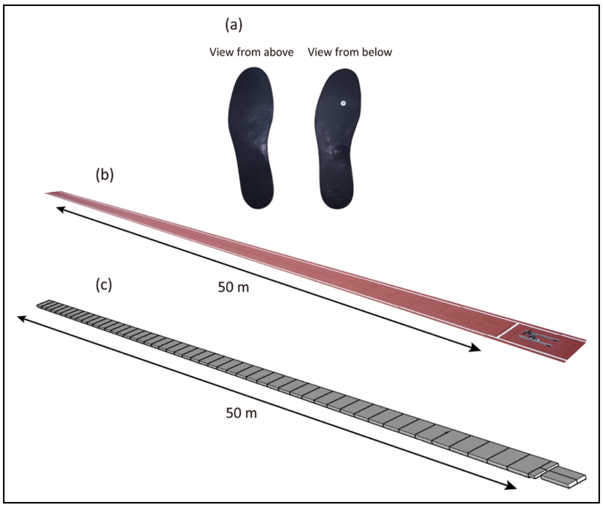

Figure 1. (a) Pictures of the sensor insole, (b) the long-force platform system and (c) sketch of the long-force platform system. Each force platform is covered by the same material as used for athletic track surface. Note that while 54 force platforms are shown (50 for the running lane and 4 for the starting position), only 50 were used in this study to collect data during sprinting after the block clearance.

Data processing and statistics

The vertical GRF signal was filtered using a Butterworth low-pass digital filter at a cut-off frequency of 50 Hz.[3] The integrated plantar pressure signal exported from the operating software was interpolated to 1000 Hz (Figure 2). Foot strike and toe-off instants during sprint acceleration from the first foot contact after the start were detected using a threshold set at 200 N for both devices because slight increase in plantar pressures occurred for some trials before the assumed foot strike instant (Figure 2(b)). For the sensor insole data, the foot strike and toe-off instants for left and right sensor insoles were separately detected

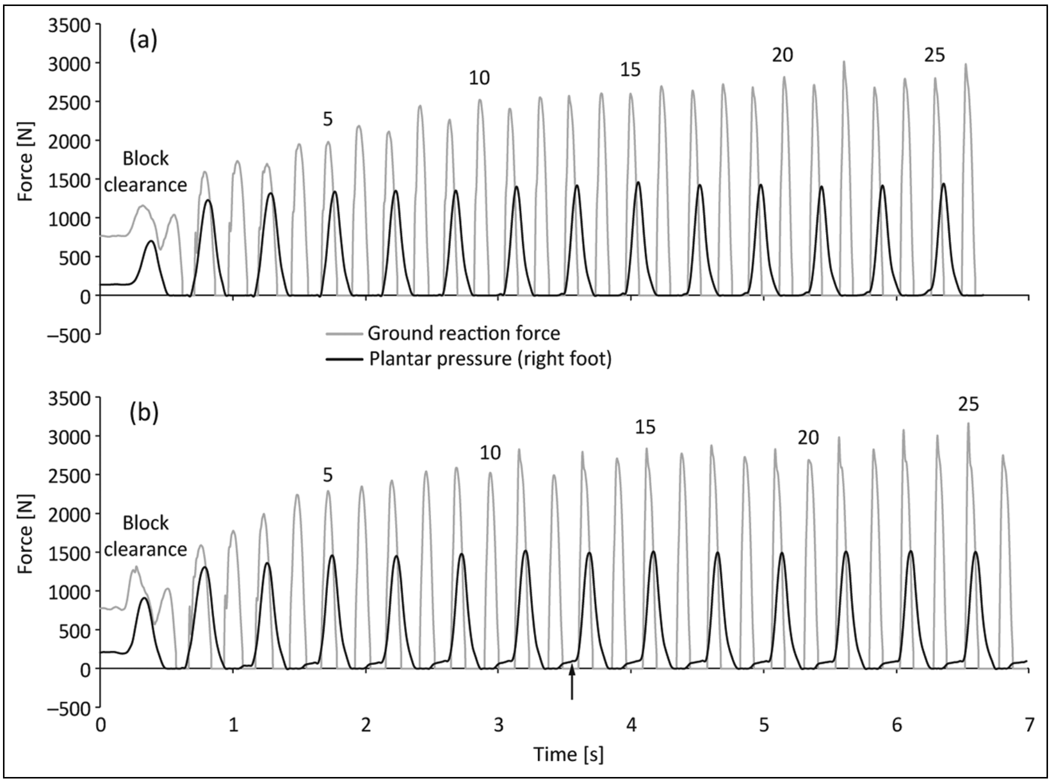

Figure 2. Vertical GRF and right foot plantar pressure signals during sprint acceleration for typical trials. (a) A trial without slight increases in plantar pressures before the assumed foot strike instant and (b) a trial with slight increases in plantar pressures before the assumed foot strike instant. The numbers in each panel indicate step numbers from the first step after the block clearance. Up-pointing arrow shows an atypical increase in plantar pressure before the foot strike.

with each pressure signal which were then integrated into a series of instants. Each step duration was determined from the foot strike of one leg to the next foot strike of the other leg. SF was calculated as the inverse of step duration. ST was defined as the duration of foot contact with the ground, and flight time (FT) was defined as the duration of no foot contact with the ground. Time to maximal vertical force from the foot strike (tFmax) was obtained. Fmax, Fmean and vertical impulse during each support phase were obtained from each of the vertical GRF and plantar pressure signals.

The variables were obtained for 25 steps after the block clearance for each trial, totaling 125 steps. Bland–Altman plots were constructed to examine agreement between variables from the sensor insole and FPs.[12,13] The mean and standard deviation were reported for all variables, and the percentage bias, 95% limits of agreement (LoA)[13] and Pearson's correlation coefficients between values from the sensor insole in relation to FP were calculated. Moreover, to examine the difference between the values from the two devices, a paired t-test was performed. In addition, the correlation coefficient between the difference and mean of values from the two devices was computed to examine heteroscedasticity. The significance level was set at $p < 0.05$.

Results

The signals of the plantar pressure measured by the sensor insole during sprinting clearly showed underestimation of the value in comparison to vertical GRF, especially at higher speeds (Figure 2). The percentage bias, 95% LoA and Bland–Altman plots showed low validity for all variables, except for SF (Figure 3, Table 1). For the vertical GRF variables, sensor insole underestimated the values (−18.9 to −48.3% on average) compared to FP. While ST and tFmax were overestimated by the sensor insole (54.6 ± 8.0% and 94.2 ± 23.2%, respectively), FT was underestimated (−48.2 ± 15.0%). Moreover, the t-test revealed a significant difference in values between sensor insole and FP, except for SF (Table 1). The bias of SF (0.4 ± 7.5%) was small. However, there were heteroscedasticities for all variables.

Discussion

This study investigated the concurrent validity of a wireless pressure sensor insole for measuring temporal and vertical force variables during sprinting. Overall, the temporal and vertical force variables measured using sensor insoles during sprinting did not provide

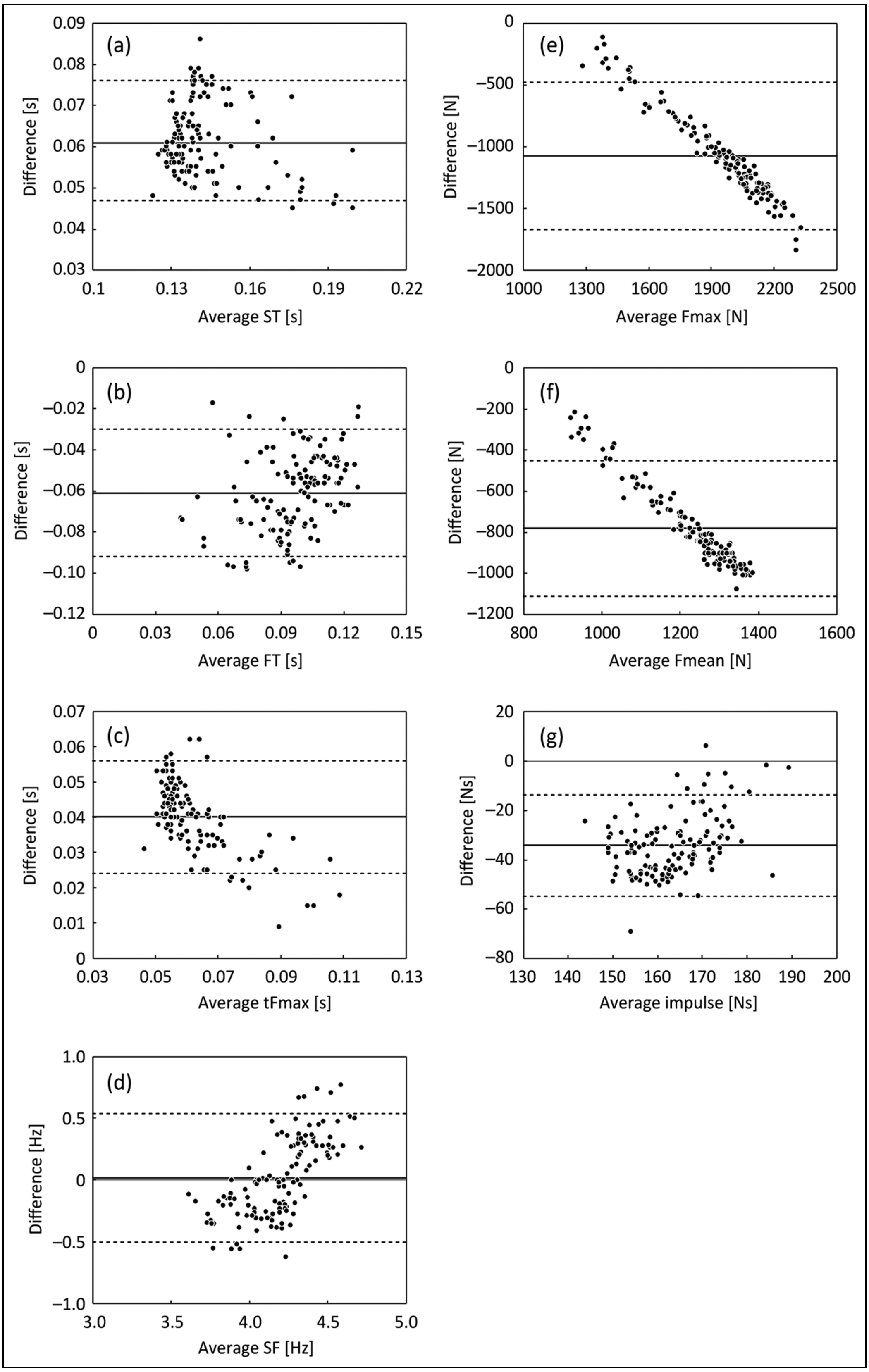

Figure 3. Bland–Altman plots of FP and sensor insole data for (a) ST, (b) FT, (c) tFmax, (d) SF, (e) Fmax, (f) Fmean and (g) impulse. The solid central line represents the average difference between instruments, while the upper and lower dotted lines represent 95% limits of agreements.

ST: support time; FT: flight time; tFmax: time to maximal vertical force from the foot strike; SF: step frequency; Fmax: maximal vertical force; Fmean: mean vertical force.

Table 1. Comparison of temporal and vertical force variables from force platform and sensor insole for ST, FT, tFmax, SF, Fmax, Fmean and impulse.

Variables (unit)	Force platform	Sensor insole	% Bias	95% LoA	t-test	Correlation coefficient (p value)	Heteroscedasticity (p value)
ST (s)	0.112 ± 0.018	0.174 ± 0.016	54.6 ± 8.0	0.047 to 0.076	< 0.001	0.863 (< 0.001)	−0.240 (0.007)
FT (s)	0.127 ± 0.017	0.066 ± 0.023	−48.2 ± 15.0	−0.092 to −0.030	< 0.001	0.598 (< 0.001)	0.361 (< 0.001)
tFmax (s)	0.042 ± 0.016	0.082 ± 0.009	94.2 ± 23.2	0.024 to 0.056	< 0.001	0.804 (< 0.001)	−0.681 (< 0.001)
SF (Hz)	4.19 ± 0.17	4.21 ± 0.36	0.4 ± 7.5	−0.503 to 0.539	0.531	0.500 (< 0.001)	0.691 (< 0.001)
Fmax (N)	2480 ± 422	1405 ± 77	−43.4 ± 14.6	−1673 to −478	< 0.001	0.827 (< 0.001)	−0.978 (< 0.001)
Fmean (N)	1620 ± 216	838 ± 31	−48.3 ± 12.3	−1111 to −454	< 0.001	0.612 (< 0.001)	−0.975 (< 0.001)
Impulse (N s)	180.4 ± 8.6	146.2 ± 12.6	−18.9 ± 6.9	−54.8 to −13.5	< 0.001	0.355 (< 0.001)	0.385 (< 0.001)

ST: support time; FT: flight time; tFmax: time to maximal vertical force from the foot strike; SF: step frequency; Fmax: maximal vertical force; Fmean: mean vertical force; LoA: limits of agreement.

accurate results. Therefore, the hypothesis of this study is not supported.

The percentage bias and 95% LoA showed a substantial underestimation of vertical GRF variables for the sensor insole. Moreover, although correlation coefficients of Fmax and Fmean between devices were relatively high, Bland–Altman plots showed clear heteroscedasticities. These heteroscedasticities indicate that the magnitude of underestimation of sensor insole for Fmax and Fmean becomes large when applied vertical GRF increases. This feature of the sensor insole can also be seen in Figure 2. ST, FT and tFmax were largely over-, under- and overestimated by the sensor insole, respectively. Moreover, although correlation coefficients of ST, FT and tFmax between devices were relatively high, there were heteroscedasticities for all three variables. The heteroscedasticities indicate that the deviations of ST, FT and tFmax measured by the sensor insole increase when ST, FT and tFmax, respectively, decrease, increase and decrease. While SF showed small percentage bias and 95% LoA, there was heteroscedasticity, indicating higher SF is accompanied by greater overestimation.

The underestimation of force variables and overestimation of tFmax during sprinting correspond to a previous study of running and jumping tasks that used the same sensor insole.[7] Both studies suggest the limitation of the sensor insole used. For ST, however, the deviation of the value measured by sensor insole was substantially greater in this study for sprinting than in a previous study for running task.[7] This difference probably resulted from the difference in ST and applied force (0.112 ± 0.018 s and 2480 ± 422 N (Fmax) in this study vs 0.340 ± 0.040 s and 1701 ± 366 N (Fmax) used in the previous study). In addition, the bias of ST during sprinting in this study was substantially greater than that in a previous study which used a custom-built sensor insole.[9] This discrepancy is likely due to the differences in sampling frequency (50 Hz in this study vs. 2500 Hz in the previous study) and configurations between two sensor insoles. The sensor insole in the previous study was specialized in detecting the foot strike and toe-off instants during sprinting, while the sensor insole in this study had general versatility for measurements.

The overall results of this study show that the validity of the sensor insole becomes low when ST decreases and applied vertical GRF increases. When the greater vertical force is exerted within a short duration, the profile of plantar pressure delays. This delayed profile resulted in longer ST and shorter FT of the sensor insole compared to FP. Moreover, this delayed profile of the sensor insole data at high speed is also probably responsible for the heteroscedasticity of SF, because high SF is accompanied by short ST.[1,2] The deviations of ST and FT from the reference can be considered to be compensated for small bias of SF as is the case in a previous study.[14]

For some trials, there were slight increases in plantar pressures before the assumed foot strike instants (Figure 2(b)). A similar phenomenon was noted in a previous study,[7] as plantar pressure value during the flight phase between jumping and landing did not fall to zero. This unexpected increase in plantar pressure is possibly caused by the downward acceleration of the foot toward the foot strike and/or pre-activity of leg and foot muscles that induce foot motion/pressure within the shoe, although this did not happen for some trials. The reason for the random unexpected increase in plantar pressure could be due to a slight difference in the position of the foot in the shoe.

Regarding limitations of this study, the sampling frequency (50 Hz) of the sensor insole was not high enough to collect pressure data during the support phase of sprinting, especially at higher speeds, because the ST at the maximal speed phase was approximately 0.1 s. As mentioned above, since this study aimed to compare temporal and GRF variables during sprinting obtained using two devices, many participants were not necessary. However, the possibility exists that the degree of conformance between a foot and shoe is not the same for all athletes. While the participant did not feel uncomfortable wearing the shoe with the sensor insole, there may not have been a perfect fit between the sensor insole and the athlete's foot. Moreover, this study only investigated the athlete wearing socks and spiked shoes. Thus, wearing running shoes without spikes without socks, running shoes without spikes with socks or spiked shoes without socks might provide different results.

Conclusion

In conclusion, this study demonstrates that a wireless pressure sensor insole is generally not valid for measuring the temporal and vertical force variables during sprinting.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship and/or publication of this article.

ORCID iD

Ryu Nagahara https://orcid.org/0000-0001-9101-9759

References

1. Nagahara R, Naito H, Morin JB, et al. Association of acceleration with spatiotemporal variables in maximal sprinting. *Int J Sports Med* 2014; 35: 755–761.
2. Weyand PG, Sternlight DB, Bellizzi MJ, et al. Faster top running speeds are achieved with greater ground forces not more rapid leg movements. *J Appl Physiol* 2000; 89: 1991–1999.
3. Nagahara R, Mizutani M, Matsuo A, et al. Association of step width with accelerated sprinting performance and ground reaction force. *Int J Sports Med* 2017; 38: 534–540.
4. Rabita G, Dorel S, Slawinski J, et al. Sprint mechanics in world-class athletes: a new insight into the limits of human locomotion. *Scand J Med Sci Sports* 2015; 25: 583–594.
5. Braun BJ, Veith NT, Hell R, et al. Validation and reliability testing of a new, fully integrated gait analysis insole. *J Foot Ankle Res* 2015; 8: 54.
6. Oerbekke MS, Stukstette MJ, Schutte K, et al. Concurrent validity and reliability of wireless instrumented insoles measuring postural balance and temporal gait parameters. *Gait Posture* 2017; 51: 116–124.
7. Stoggl T and Martiner A. Validation of Moticon's OpenGo sensor insoles during gait, jumps, balance and cross-country skiing specific imitation movements. *J Sports Sci* 2017; 35: 196–206.
8. Dorn TW, Schache AG and Pandy MG. Muscular strategy shift in human running: dependence of running speed on hip and ankle muscle performance. *J Exp Biol* 2012; 215: 1944–1956.
9. Kuntze G, Pias M, Bezodis I, et al. Custom-built wireless pressure sensing insoles for determining contact-times in 60m maximal sprint running. In: *Proceedings of 27th International Symposium on Biomechanics in Sport* (eds AJ Harrison, R Anderson and I Kenny), Limerick, 17–21 August 2009, pp.1–4. Konstanz: ISBS.
10. Balsalobre-Fernandez C, Agopyan H and Morin JB. The validity and reliability of an iPhone app for measuring running mechanics. *J Appl Biomech* 2016; 33: 222–226.
11. Morin JB and Belli A. A simple method for measurement of maximal downstroke power on friction-loaded cycle ergometer. *J Biomech* 2004; 37: 141–145.
12. Bland JM and Altman DG. Measuring agreement in method comparison studies. *Stat Methods Med Res* 1999; 8: 135–160.
13. Querido A, Castro MP, Vilas-Boas JP, et al. Reliability and accuracy of spatial–temporal gait parameters measured by the WalkinSense®. *Proc IMechE, Part P: J Sports Engineering and Technology* 2016; 230: 275–279.
14. Gindre C, Lussiana T, Hebert-Losier K, et al. Reliability and validity of the Myotest(R) for measuring running stride kinematics. *J Sports Sci* 2016; 34: 664–670.