Published in "Journal of Strength and Conditioning Research
doi: 10.1519/JSC.0000000000001299, " which should be cited to refer to this work.

Accuracy of PARTwear inertial sensor and Optojump optical measurement system for measuring ground contact time during running

Brief running head:

Ground contact time accuracy in portable measurement systems

Authors:

Rahel Ammann[1,2], Wolfgang Taube[2], Thomas Wyss[1]

[1]Swiss Federal Institute of Sport Magglingen SFISM, Magglingen, Switzerland

[2]University of Fribourg, Department of Medicine, Movement and Sport Science, Fribourg

Corresponding Author:

Rahel Ammann

Hauptstrasse 247, CH-2532 Magglingen

Phone: +41 58 467 63 21

Fax: +41 58 467 63 56

Rahel.Ammann@baspo.admin.ch

Abstract: The aim of this study was to validate the detection of ground contact time (GCT) during running in two differently working systems: a small inertial measurement sensor, PARTwear (PW), worn on the shoe laces, and the optical measurement system, Optojump (OJ), placed on the track. Twelve well-trained subjects performed 12 runs each on an indoor track at speeds ranging from 3.0 - 9.0 m·s-1. GCT of one step per run (total 144) was simultaneously obtained by the PW, the OJ, and a high-speed video camera (HSC), whereby the latter served as reference system. The sampling rate was 1,000 Hz for all methods. Compared to the HSC, the PW and the OJ systems underestimated GCT by -1.3 ±6.1% and -16.5 ±6.7% (p-values < .05), respectively. The intraclass correlation coefficients between PW and HSC and between OJ and HSC were .984 and .853 (p-values < .001), respectively. Despite the constant systematic underestimation of GCT, analyses indicated that PW successfully recorded GCT over a wide range of speeds. However, results showed only moderate validity for the OJ system, with increasing errors when speed decreased. In conclusion, the PW proved to be a highly useful and valid application, and its use can be recommended not only for laboratory settings but also for field applications. In contrast, data on GCT obtained by OJ during running must be treated with caution, specifically when running speed changes or when comparisons are made with GCT data collected by other measurement systems.

Keywords: inertial measurement unit, field-based application, running, monitoring training

INTRODUCTION

When running, the only moment to generate propulsive force is during the ground contact time (GCT), which is the period between the initial contact with the ground and the subsequent toe-off. The ability to produce and transmit high amounts of muscular force to the ground over a short period of time is a major determinant of performance in running (37, 38). It has been demonstrated that runners with shorter GCT were not only faster but also more energy efficient than runners with longer GCT (27, 34). Kong and colleagues (23) argued that shorter GCT might be related to good running economy because there is less time for the braking force to decelerate forward motion of the body. This can be based on the mass-spring model of running, which states that higher leg stiffness results in shorter GCT. Less economical runners are shown to have a more slacken running style during ground contact as reflected by the low vertical stiffness (21). Morin and coworkers (25) demonstrated that 90 - 96% of the variance in leg stiffness can be explained by GCT, whether GCT is directly controlled, or indirectly controlled through its close relationship with step frequency (25). Generally, with increasing speed the GCT decreases (6, 19, 20, 29, 38). An increase in speed of 0.6 $m \cdot s^{-1}$ usually results in a GCT decrease of 15 to 28 ms. However, it has been shown that even at an equivalent speed, sprinters have a shorter GCT than distance runners (11, 36). This might be due to differences in their muscle fiber distribution and striking patterns. Notwithstanding, having the ability to decrease GCT may benefit distance runners and sprinters during certain stages of their races and can make the distinction between becoming first or second. Fast running over whichever distance depends on many factors, such as force application, stretch-shortening cycle, joint angle, or step frequency. Yet, at the end it comes all down to the ground contact, because only during that time the propulsive ground reaction force impulse can be generated. Moreover, by measuring GCT during an entire course of a run, asymmetries in running style and changes due to fatigue can be detected. Hence, objective information on GCT could be relevant to monitor and regulate the training of athletes. On one hand, shorter GCT can be the training target, for instance during acceleration or final stages of a course. On the other hand, shorter GCT can be the training outcome to evaluate if a training intervention, such as a specific exercise, was successful.

To assess GCT, many different devices, such as force plates, optical timing systems, and optical motion capture systems, have been used (6, 12, 13, 16, 36). From these previous investigations, video techniques and force plates were recommended as the gold standard to measure GCT or flight time (e.g. to determine vertical jump height; 1, 10, 22, 29, 33). Of these two systems, video has the advantage of high spatio-temporal resolution to clearly determine and visualize the phase of contact without the need to pre-process (e.g. filter) the data. In contrast, data obtained from force plates rely on filtering methods and step detection thresholds that may significantly affect GCT (10, 15). In general, data collection with the aforementioned devices mostly takes place in laboratory settings or at least in confined conditions due to the sensitivity of the devices and/or the need for a standardized infrastructure. Furthermore, the measurement area is often limited, allowing the assessment of only a few steps. Besides the costly laboratory setting, the acquisition, maintenance costs, and expertise to operate such gold standard systems are additional factors that hamper their implementation on a regular basis in field situations. However, training assessment in field situations is important because treadmills do not perfectly simulate natural running and cannot replicate outdoor conditions (26). Furthermore, laboratory tests mostly take place on an infrequent basis, 1 to 2 times a year, which is not practical for an ongoing training routine or during periods of thematic priority (39). If specific emphases are set, immediate and frequent feedback is necessary to verify changes in performance and to understand how a specific technique/skill is changed (3). Objective information on GCT, in terms of augmented feedback is needed, because neither the athlete, the coach nor the researcher can accurately perceive GCT without the help of an external measurement system. Furthermore, to gain more insight in the area and consequences of GCT, more regular field based data, over entire training and competition distances and not only a few steps, are required. Hence, there is a need for affordable, light-weighted, and easy to operate systems that reliably and precisely measure GCT in real time.

There are devices on the market that measure GCT outside the laboratory (4, 7). These are either small, body-wearable inertial measurement sensors, or portable optical timing systems which can be placed on the track. In previous studies, systems measuring parameters of vertical jump performance, like flight time, jumping height, or GCT, were validated and their measurement errors were quantified (8, 15, 17, 32). However, to date, it is not clear whether these results can be transferred to running, where acceleration changes occur not only in a vertical but also in a horizontal direction. This additional horizontal direction leads to different foot angles during initial ground contact and toe-off and much shorter GCT than in vertical jumping. Furthermore, the different running disciplines require a wide range of running speeds. Hence, the variety of movement velocity is much greater in running than in jumping. Evaluated measurement systems, such as inertial measurement units or photocell mats, showed limitations in the estimation of accurate GCT depending on running speed (29, 36).

Hence, the aim of the present study was to investigate the concurrent validity of a new inertial measurement sensor and an established optical measurement system to detect GCT during running on an indoor track. For this purpose, data were collected at different running speeds and compared to the data obtained with a high-speed video camera.

METHODS

Experimental Approach to the Problem

The experimental devices to measure GCT were the inertial measurement sensor PARTwear (PW; HuCE-microLab, University of Applied Sciences, Biel, Switzerland) and the optical measurement system Optojump (OJ; Optojump Next, Microgate, Bolzano, Italy). As gold standard, a high-speed video camera system (HSC; Camera Marathon Ultra CL600, Videal AG, Niederönz, Switzerland) was used. Data assessment took place on a completely even indoor track and participants wore their own running spikes, alike during competition. To ensure measurement system accuracy for a range of speeds, each subject was asked to perform three sets of four runs over a distance of 40 m at individual maximal sprinting, intense, and normal training speed. Speeds were self-selected to allow for natural running technique. For each run, one step was analyzed 30 m from the start. To test the PW's and OJ's validity, GCT were simultaneously registered by all three measurement systems worn by the same subject.

Subjects

Five female and seven male volunteers (25.3 ±3.2 years, 174.4 ±7.9 cm, 64.8 ±10.2 kg) were recruited to participate in this study. All volunteers were high-level running athletes, of whom six were athletes of the xy national middle distance squad. Furthermore, they were all familiar with the procedure, the possible risks involved, and gave their written informed consent before data collection. The Institutional Review Board of the Federal Office of Sport, in accordance with the Declaration of Helsinki, approved the study protocol.

Equipment/Devices

The PW sensor is relatively small (3.8 x 3.7 x 0.8 cm) and light (13 g) and it is fixed to the lace of the shoe. The sensor consists of a 9-axis MotionTracking™ device MPU-9150 (InvenSense, Inc., San Jose, CA, USA) that combines a 3-axial accelerometer, a 3-axis gyroscope, and a 3-axis magnetometer. Accelerometer data was recorded with a full-scale range of ±16 g and a sampling rate of 1,000 Hz. Data transmission was established via Bluetooth and data processing took place by the proprietary software (HuCE-microLab, University of Applied Sciences, Biel, Switzerland). The respective algorithm recognized patterns in the acceleration signal collected on the foot, such as local minima and maxima, to determine initial ground contact and toe-off. The second device, the optical measurement system OJ, consists of two 100 x 4 x 3 cm bars with a sampling rate of 1,000 Hz. The OJ bars communicate continuously by optical light-emitting diodes (LEDs), whereby the bars function as both transmitting and receiving units for the LED signals. Each of the bars contains 96 LEDs, positioned 3 mm from ground level at 1.04 cm intervals. The system detects any interruption in communication between the LEDs and thereby derives the GCT. The system was connected via USB to a personal computer and data were processed by the proprietary software (Optojump software, version 1.9.0, Microgate, Bolzano, Italy). The high-speed video camera (HSC) MarathonUltra with 1,000 Hz sampling rate and an image size of 800 x 600 served as the reference device. To ensure the best possible light conditions for the HSC lens, additional lights spotlighted the setup. For the offline evaluation of GCT of every videotaped step, the motion analysis software MarathonPro (Videal AG, Niederönz, Switzerland) was used. Average horizontal speed over the course of each trial was assessed using portable timing lights (Witty timer, Microgate, Bolzano, Italy).

Procedures

Participants were asked to avoid strenuous training the day prior to testing and to bring their own running shoes with spikes. On the test day, participants performed the warm-up protocol they usually follow before performing maximal sprints. Then, participants were equipped with two PW sensors, tightly fixed by elastic straps to the laces of each shoe. Subsequently, subjects performed three sets of four 40 m runs on an indoor track. The three speeds were introduced as being representative of individual maximal sprinting, intense, and normal training. The measurements took place in that order to ensure that athletes warmed-up adequately, hence, to prevent injury. A rest period of at least 3 min was provided between trials. In the first 20 m, subjects accelerated so they could maintain a constant running speed throughout the following 20 m. The running speed was measured over the second 20 m by timing lights placed 1.2 m high. The OJ bars and HSC were installed 30 m from the starting line. The HSC was placed at surface level at a distance of 2 m from the track. The limited area of 1 x 1 m, where the HSC and the OJ recorded data, was marked with yellow tape and well-lighted by extra spotlights. Subjects were instructed to run naturally over this 1 x 1 m area. If the participants failed to hit the marked area or performed an unnatural step to hit the target, the trial was repeated after the 3 min recovery time. For each valid trial, one step was simultaneously recorded by the PW, the OJ, and the HSC and analyzed offline. The analysis of the GCT of every videotaped step was executed on-screen by visual inspection through three independent observers. The GCT was obtained from the first frame where the foot landed on the ground until the last frame before take-off. The three observers stated no difficulties in defining initial foot contact and toe-off. In the few cases of inter-rater differences of more than 3 ms per GCT, the steps were reanalyzed. According to Hasegawa et al. (19) all evaluated steps were considered as either forefoot or midfoot strikes.

Statistical Analysis

According to the present research design, each step was entered into the calculation as a single case. The mean values and standard deviations of the runs were retained for each measurement system. For each measurement system a total of 12 out of 144 values were excluded from the analyses due to a technical failure of one of the devices. Normality of the data was assumed because the ratio of skewness to the standard deviation of skewness did not exceed ±2.0. Concurrent validity of the PW and the OJ were investigated using intraclass correlation coefficients (ICCs) with 95% confidence intervals and Bland and Altman systematic bias ±random errors. Bland and Altman plots were used to visualize systematic differences in GCT predictions. The systematic bias represents the absolute difference between the measurement systems, and the random errors are calculated by the standard deviations of the difference between PW and HSC and OJ and HSC, respectively, and then multiplied by 1.96. Together they form the 95% limits of agreement (2, 5). Furthermore, a repeated measures ANOVA was executed to evaluate the occurrence of systematic differences between the measurement systems (independent variables) on GCT (dependent variable), followed by Bonferroni-corrected post hoc analyses in case of significant overall effects. Mauchly’s test was applied to assess sphericity. Cohen’s d effect sizes were calculated using means and standard deviations to assess meaningfulness of differences (9, 14). The effect sizes of > 0.8, 0.8 - 0.5, 0.5 - 0.2, and < 0.2 were regarded as large, moderate, small, and trivial, respectively. Pearson tests were employed for the calculation of correlations between GCT and speed, and also between GCT and absolute differences. To evaluate reproducibility, inter-trial reliability was assessed with ICCs and coefficients of variation (CVs) over all runs separated according to the three relative running speeds. The ICCs and CVs of the PW and the OJ were compared with the values computed by the HSC. The statistical analyses were executed with SPSS 22.0 (Inc., Chicago, IL, USA) and the results were considered as significant if $p \leq .05$.

Table 1 about here

RESULTS

The mean GCT of all analysed steps measured by the PW, the OJ, and the HSC were 149.3 ±35.8 ms, 127.1 ±32.4 ms, and 152.9 ±39.3 ms, respectively (Table 1). Considering all running speeds, shorter GCT were registered for both the PW (-1.3 ±6.1%) and the OJ (-16.5 ±6.7%) compared to the HSC. The systematic bias ±random errors and ICCs can be observed in Table 2 and Figure 1. Repeated measures ANOVA for all running speeds showed the occurrence of significant systematic differences between the three measurement systems F (1.63, 218.73) = 365.93, $p < .05$. As Mauchly's test indicated that the assumption of sphericity had been violated χ^2 (2) = 33.94, $p < .001$, the Greenhouse-Geisser corrected tests were reported ($\varepsilon = .82$) for the repeated measures ANOVA. The differences between the PW and the HSC were considered as trivial (.10) and between the OJ and the HSC as moderate (.72). In all devices, shorter GCT were registered when the running speed increased. Significant correlations (all p-values < .001) between speed and GCT were revealed within the PW (r = -.847), the OJ (r = -.816), and the HSC (r = -.897), respectively. The correlation between the absolute difference and the mean was non-significant between the PW and the HSC (r = -.137, p = .112) but significant (r = -.518, $p < .001$) when comparing the OJ with the HSC. With increasing respective mean values for GCT, the difference between the OJ and the HSC increased (Figure 1). The inter-trial ICCs of GCT per speed were high and similar within the PW (.911 - .960) and the OJ (.951 - .971) to those calculated for the HSC (.864 - .978). In the same way, the CVs were relatively low and similar among all three systems ranging from 2.9 – 3.8%, 2.5 – 3.3%, and 2.6 – 3.0% in the PW, the OJ, and the HSC, respectively.

Table 2 and Figure 1 about here

DISCUSSION

This study sought to examine the validity of the inertial measurement sensor PW and the optical measurement system OJ, when obtaining GCT on an indoor track at different running speeds. The major findings of the present investigation were that the PW demonstrated strong concurrent validity, whereas the OJ showed less valid GCT recordings compared to data measured with the HSC. The PW and the OJ underestimated the GCT compared to the HSC, resulting in trivial and moderate Cohen’s d effect sizes, respectively.

The PW has only recently been introduced to the market and, as such, previous research has not addressed the validity of this system. Our results show a small, but significant underestimation (-1.3 ±6.1%) of the GCT. A possible explanation for the underestimation might be a bias in the detection of toe-off by the sensor algorithm (24, 30). It was stated that the signal at toe-off is not as pronounced as the initial contact, particularly at higher speeds, resulting in shorter GCT. This would be in line with the present results displaying the lowest ICC between the PW and the HSC at maximal speed (ICC = .808, CI95% .653 - .894). Yet, the overall ICC between the PW and the gold standard for the whole range of velocities was very strong (ICC = .984, CI95% .977 - .989), indicating a good practical application. Furthermore, the differences were systematic, that is, the PW algorithm seemed to be consistently valid across running speeds (3.0 – 9.0 $m \cdot s^{-1}$). This is an important finding as a previous study suggested that measurement errors during sprint running cannot automatically be extended to distance running when using inertial measurement sensors (4). They argued that the higher explosiveness in sprint running compared to distance running leads to differences in shock, vibration, and/or damping that would affect measurement accuracy. However, it has to be mentioned that previous studies evaluating inertial measurement sensors faced some serious limitations as either the sensor or the reference system or both operated at low temporal resolution (4, 31). Lastly, previous studies also revealed that the more distal the sensor was located (i.e., the closer the sensor was to the foot) the more accurate the detection of GCT (30). In the present study, the PW was fixed on the shoe, which probably contributed to the high measurement accuracy across running speeds.

The OJ is an established testing device. The system is portable, though data acquisition is limited to a confined area and straight tracks. Despite its popular application, the OJ has only been validated so far for vertical jumps (8, 17). In the present study, significant lower GCT values (-16.5 ±6.8%) were registered by the OJ than by the HSC. Moreover, the differences were affected by the running speed. Slower speeds induced a greater underestimation of GCT. This finding is in accordance with Ogueta-Alday et al. (29) who revealed in their study that contact differences between a contact laser system and an HSC decreased when running speed increased and stabilized above 4.5 $m \cdot s^{-1}$. Similar findings were reported by Viitasalo et al. (36). They explained this phenomenon by the faster foot speed during initial contact and toe-off at higher velocities resulting in more reliable contact values. It was assumed that the height of the measurement system from ground level could be neglected with increased foot speed. Noteworthy, when using the OJ for the detection of GCT during vertical jumps and not during running, an overestimation of the GCT was observed (18, 29, 36). This overestimation was explained by the fact that the LEDs from the OJ bars are placed at a relative height of approximately 3 mm from the ground, thus, resulting in a total of 6 mm vertical travel distance that is considered as ground contact although the subject is airborne. It was therefore previously argued that this LED raise with respect to the ground causes an interruption of the transmitter-receiver circuit slightly before the foot lands and slightly after it takes off; thus, resulting in an overestimation. It is now difficult to explain the opposite effect; the underestimation of GCT observed in the present running study. There is no comparable data available testing the OJ system with spikes. The spikes might have irritated the LEDs e.g., the reflection at landing and toe-off. Furthermore, the underestimation might be due to random variations in switching on/off of the optical bars during ground contact (8). In other words, the 1.04 cm interval of LEDs might not be recurrent enough. Or else, due to the forefoot or midfoot strikes, subjects' heels only partly touched the ground during an entire ground contact or intermittently interrupted the transmitter-receiver circuit, respectively. This might have caused measurement errors in the OJ system. However, we can only speculate that one or more of the aforementioned factors might have biased the calculation of GCT greater at slower running speeds when using the OJ. Nevertheless, the current results indicate that the underestimation by the OJ makes a comparison across studies and measurement systems problematic.

Good reliability was demonstrated for both evaluated systems. The ICCs and CVs were very similar among all measurement systems. The slight differences in running speed between individuals and trials reflected variations as they occur in a natural testing situation like in the present study. Due to the fact that each step was simultaneously measured by all three devices, worn by the same subject, we are confident that reliability for each device holds. The confirmation of the reproducibility allows strength and conditioning professionals to be confident of using the PW or OJ to measure GCT, whereby measured changes in GCT would reflect true changes in GCT.

The strength of the present study is the usage of a very sophisticated HSC as gold standard, with a high frequency and high resolution (35). Moreover, the installation of the HSC at surface level allowed for untainted determination of exact ground contact. Furthermore, as the monitoring of GCT is mainly important for high-level runners, only these specific subjects were recruited (28).

PRACTICAL APPLICATIONS

Monitoring GCT is important to strength and conditioning professionals, as GCT explains 90 – 96% of the variance in leg stiffness (25). Higher leg stiffness in turn is related to better running economy. The regular measurement of GCT can help design training sessions to improve running technique, such as GCT itself or a related parameter. The results demonstrated that the PW is a valid and accurate method to assess GCT. Indeed, the ICCs between the PW and the HSC were very high. Considering practical and clinical significance, the PW has the advantage of being much more feasible than a HSC and appears to be a promising device for athletes and coaches to regularly monitor field training sessions for the following reasons: First, athletes are hardly affected by the sensors during training due to their small size, light weight, and simple mounting on the shoe laces; Second, the PW can record GCT at every step, without the limitations of track length or running direction (e.g. curves), which would mean a high practical interest for athletes, coaches, and researchers. As an example, asymmetries can be detected, the course of fatigue, or small differences between subjects or situations; Third, the PW has the potential to support real-time training monitoring for a group of athletes, whereas the HSC, the OJ, and most other systems can only measure one athlete at a time; Fourth, due to its consistency over a wide range of running speeds, the PW can be used by athletes at different levels and disciplines i.e., short and long distances.

The OJ system proved to be less accurate for the detection of GCT during running, and therefore, seems less valid for the interchangeable use in sports and research. Surprisingly, the good measurement accuracy of the OJ reported for vertical jumps cannot be confirmed when assessing GCT in running. It seems that different requirements are needed for the accurate detection of GCT while running with spikes in a horizontal direction. Nevertheless, our data indicate a good reliability, hence, the OJ system can still be recommended for the systematic monitoring of GCT during training. In addition, the capability of this system to measure other parameters, such as step frequency, step length, flight time, etc., highlights the potential of the OJ as an effective measurement tool for strength and conditioning professionals. However, the comparison of GCT values obtained with the OJ with those from other devices is not recommended.

ACKNOWLEDGMENTS

The authors thank the runners and the xy Athletics Federation for participation. The authors have no conflict of interest to disclose. The information provided does not constitute endorsement by the National Strength and Conditioning Association.

REFERENCES

1. Aragón LF. Evaluation of four vertical jump tests: Methodology, reliability, validity, and accuracy. *Meas Phys Educ Exerc Sci* 4: 215-228, 2000.

2. Atkinson G and Nevill AM. Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. *Sports Med* 26: 217-238, 1998.

3. Austin KG and Deuster P. Monitoring training for human performance optimization. *J Spec Oper Med* 15: 102-108.

4. Bergamini E, Picerno P, Pillet H, Natta F, Thoreux P, and Camomilla V. Estimation of temporal parameters during sprint running using a trunk-mounted inertial measurement unit. *J Biomech* 45: 1123-1126, 2012.

5. Bland JM and Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet* 8: 307-310, 1986.

6. Bushnell T and Hunter I. Differences in technique between sprinters and distance runners at equal and maximal speeds. *Sports Biomech* 6: 261-268, 2007.

7. Casartelli N, Muller R, and Maffiuletti NA. Validity and reliability of the Myotest accelerometric system for the assessment of vertical jump height. *J Strength Cond Res* 24: 3186-3193, 2010.

8. Castagna C, Ganzetti M, Ditroilo M, Giovannelli M, Rocchetti A, and Manzi V. Concurrent validity of vertical jump performance assessment systems. *J Strength Cond Res* 27: 761-768, 2013.

9. Cohen J. *Statistical power analysis for the behavioral sciences*. Hillsdale, N.J.: L. Erlbaum Associates, 1988.

10. Cronin JB and Rumpf MC. Effect of four different step detection thresholds on nonmotorized treadmill sprint measurement. *J Strength Cond Res* 28: 2996-3000, 2014.

11. Cunningham R, Hunter I, Seeley M, and Feland B. Variations in running technique between female sprinters, middle, and distance runners. *Int J Exerc Sci* 6: 43-51, 2013.

12. Debaere S, Jonkers I, and Delecluse C. The contribution of step characteristics to sprint running performance in high-level male and female athletes. *J Strength Cond Res* 27: 116-124, 2013.

13. Di Michele R and Merni F. The concurrent effects of strike pattern and ground-contact time on running economy. *J Sci Med Sport* 17: 414-418, 2014.

14. Field A. *Discovering Statistics Using IBM SPSS Statistics*. London: Sage Publications Ltd, 2012.

15. Garcia-Lopez J, Peleteiro J, Rodgriguez-Marroyo JA, Morante JC, Herrero JA, and Villa JG. The validation of a new method that measures contact and flight times during vertical jump. *Int J Sports Med* 26: 294-302, 2005.

16. Girard O, Millet GP, Slawinski J, Racinais S, and Micallef JP. Changes in running mechanics and spring-mass behaviour during a 5-km time trial. *Int J Sports Med* 34: 832-840, 2013.

17. Glatthorn JF, Gouge S, Nussbaumer S, Stauffacher S, Impellizzeri FM, and Maffiuletti NA. Validity and reliability of Optojump photoelectric cells for estimating vertical jump height. *J Strength Cond Res* 25: 556-560, 2011.

18. Gullstrand L and Nilsson J. A new method for recording the temporal pattern of stride during treadmill running. *Sports Eng* 11: 195-200, 2009.

19. Hasegawa H, Yamauchi T, and Kraemer WJ. Foot strike patterns of runners at the 15-km point during an elite-level half marathon. *J Strength Cond Res* 21: 888-893, 2007.

20. Hayes P and Caplan N. Foot strike patterns and ground contact times during high-calibre middle-distance races. *J Sports Sci* 30: 1275-1283, 2012.

21. Heise GD and Martin PE. Are variations in running economy in humans associated with ground reaction force characteristics? *Eur J Appl Physiol* 84: 438-442, 2001.

22. Klavora P. Vertical-jump tests: A critical review. *Strength Cond J* 22: 70-74, 2000.

23. Kong PW and de Heer H. Anthropometric, gait and strength characteristics of Kenyan distance runners. *J Sports Sci Med* 7: 499-504, 2008.

24. McGrath D, Greene BR, O'Donovan KJ, and Caulfield B. Gyroscope-based assessment of temporal gait parameters during treadmill walking and running. *Sports Eng* 15: 207-213, 2012.

25. Morin JB, Samozino P, Zameziati K, and Belli A. Effects of altered stride frequency and contact time on leg-spring behavior in human running. *J Biomech* 40: 3341-3348, 2007.

26. Nigg BM, De Boer RW, and Fisher V. A kinematic comparison of overground and treadmill running. *Med Sci Sports Exerc* 27: 98-105, 1995.

27. Nummela A, Keranen T, and Mikkelsson LO. Factors related to top running speed and economy. *Int J Sports Med* 28: 655-661, 2007.

28. Nuzzo JL, Anning JH, and Scharfenberg JM. The reliability of three devices used for measuring vertical jump height. *J Strength Cond Res* 25: 2580-2590, 2011.

29. Ogueta-Alday A, Morante JC, Rodriguez-Marroyo JA, and Garcia-Lopez J. Validation of a new method to measure contact and flight times during treadmill running. *J Strength Cond Res* 27: 1455-1462, 2013.

30. Patterson M and Caulfield B. A method for monitoring reactive strength index. *Procedia Eng* 2: 3115-3120, 2010.

31. Purcell B, Channells J, James D, and Barrett R. *Use of accelerometers for detecting foot-ground contact time during running*. Presented at BioMEMS and Nanotechnology II, Brisbane, Australia, 2005.

32. Quagliarella L, Sasanelli N, Belgiovine G, Moretti L, and Moretti B. Evaluation of standing vertical jump by ankles acceleration measurement. *J Strength Cond Res* 24: 1229-1236, 2010.

33. Requena B, Garcia I, Requena F, Saez-Saez de Villarreal E, and Paasuke M. Reliability and validity of a wireless microelectromechanicals based system (keimove) for measuring vertical jumping performance. *J Sports Sci Med* 11: 115-122, 2012.

34. Santos-Concejero J, Granados C, Irazusta J, Bidaurrazaga-Letona I, Zabala-Lili J, Tam N, and Gil SM. Differences in ground contact time explain the less efficient running economy in north african runners. *Biol Sport* 30: 181-187, 2013.

35. Taherian S, Pias M, Harle R, Coulouris G, Hay S, Cameron J, Lasenby J, Kuntze G, Bezodis I, Irwin G, and Kerwin D. *Profiling sprints using on-body sensors.* Presented at Pervasive Computing and Communications Workshops (PERCOM Workshops), 2010 8th IEEE International Conference on, March 29 2010-April 2 2010, 2010.

36. Viitasalo JT, Luhtanen P, Mononen HV, Norvapalo K, Paavolainen L, and Salonen M. Photocell contact mat: A new instrument to measure contact and flight times in running. *J Appl Biomech* 13: 254-266, 1997.

37. Weyand PG, Sandell RF, Prime DNL, and Bundle MW. The biological limits to running speed are imposed from the ground up. *J Appl Physiol* 108: 950-961, 2010.

38. Weyand PG, Sternlight DB, Bellizzi MJ, and Wright S. Faster top running speeds are achieved with greater ground forces not more rapid leg movements. *J Appl Physiol* 89: 1991-1999, 2000.

39. Wixted AJ, Billing DC, and James DA. Validation of trunk mounted inertial sensors for analysing running biomechanics under field conditions, using synchronously collected foot contact data. *Sports Eng* 12: 207-212, 2010.

Figure 1. Bland and Altman plots of the ground contact times (GCT) for all speeds: PARTwear (PW) vs. high-speed video camera (HSC; left) and Optojump (OJ) vs. HSC (right). Dashed lines show the limits of agreement, defined by the range of 1.96 standard deviations above and below the systematic bias, whereas the solid lines represent the systematic biases.

Table 1. Absolute ground contact times ±standard deviations according to speed recorded by each measurement system.

Speed	PARTwear	Optojump	High-speed video camera
	Ground contact time [ms]		
All speeds (6.2 ±1.6 m·s^{-1})	149.3 ±35.8	127.1 ±32.4	152.9 ±39.3
Maximal speed (8.0 ±0.5 m·s^{-1})	118.3 ±11.6	100.6 ±11.5	117.5 ±9.0
Intense training speed (6.2 ±0.7 m·s^{-1})	145.5 ±20.9	122.6 ±19.3	147.4 ±20.3
Normal training speed (4.3 ±0.7 m·s^{-1})	185.5 ±21.7	159.5 ±30.4	194.6 ±34.3

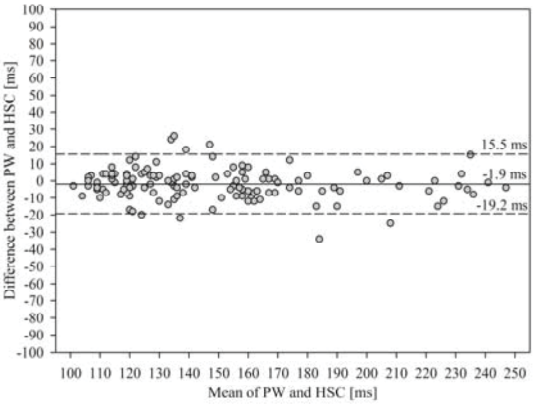
1

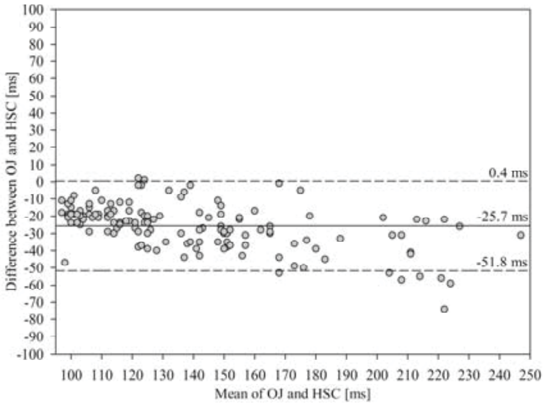
Table 2. Concurrent validity of PARTwear (PW) and Optojump (OJ) with high-speed video camera (HSC) data, respectively.

	PW vs. HSC	**OJ vs. HSC**
All speeds (6.2 ±1.6 m·s^{-1})		
Systematic bias [ms]	-1.9*	-25.7*
Random error [ms]	±17.4	±26.1
Deviation to reference [%]	-1.3 ±6.1	-16.5 ±6.7
ICC (95% CI)	.984* (.977 - .989)	.853* (-.137 - .960)
Maximal sprinting speed (8.0 ±0.5 m·s^{-1})		
Systematic bias [ms]	0.4	-17.3*
Deviation to reference [%]	-0.1 ±6.7	-14.7 ±6.9
ICC (95% CI)	.808* (.653 - .894)	.432* (-.183 - .771)
Intense training speed (6.2 ±0.7 m·s^{-1})		
Systematic bias [ms]	-0.7	-24.9*
Deviation to reference [%]	-0.8 ±6.2	-16.8 ±7.0
ICC (95% CI)	.956* (.921 - .976)	.644* (-.158 - .892)
Normal training speed (4.3 ±0.7 m·s^{-1})		
Systematic bias [ms]	-5.6*	-34.7*
Deviation to reference [%]	-3.3 ±5.0	-18.1 ±6.0
ICC (95% CI)	.973* (.916 - .988)	.731* (-.122 - .928)

Note. ICC = intraclass correlation coefficient; CI = confidence interval.
* $p < .05$.

1


15.5 ms
-1.9 ms
-19.2 ms
Difference between PW and HSC [ms]
Mean of PW and HSC [ms]


0.4 ms
-25.7 ms
-51.8 ms
Difference between OJ and HSC [ms]
Mean of OJ and HSC [ms]