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Machulik C[1], Hamacher D[2], Lindlein K[1,3], Zech A[2], Hollander K[1,4]

Validation of an Inertial Measurement Unit Based Magnetic Timing Gate System during Running and Sprinting

Validierung eines Inertialsensor-basierten Magnetschrankensystems beim Laufen und Sprinten

Summary

- **Problem:** The technology of inertial measurement units (IMU) enables the collection of running biomechanical data under in-field conditions. This paper presents a validation study of an increasingly used IMU system using a corresponding below-ground magnetic timing gate system.
- **Methods:** Thirty active healthy participants ran with an IMU located at the lumbar spine on a 60 m-section of a 400 m tartan track. The IMUs were connected with magnetic timing gates installed below the tartan track. A photoelectric cell reference system was used for comparative analysis. Outcome measures were running speed, step length and cadence during running at slow and fast velocity. Intra-Class-Correlation (ICC), Bland-Altman analysis and regression-based Bland-Altman analysis were used to determine measurement agreement.
- **Results:** The analysis showed high measurement agreement for running speed, step length and cadence for both velocities (ICCs 0.745-0.996). Bland-Altman analysis showed high random errors and increased systematic and random errors for step length and cadence at fast running velocities. Regression-based Bland-Altman analysis indicated a systematic increase of bias (systematic error) with higher step length values.
- **Discussion:** Despite a high measurement agreement expressed by ICCs, study results also showed high error values for absolute measurements expressed by systematic and random errors for all parameters. Therefore, attention should be given to the comparability of both measurement systems. Further research should focus on details of step length calculations as well as reliability and validity under longer running conditions.

Zusammenfassung

- **Problemstellung:** Inertialsensoren (IMU) bieten die technologische Möglichkeit, biomechanische Eigenschaften des Laufens unter Feldbedingungen zu erfassen. Ein hierfür entwickeltes IMU- und Magnetschrankensystem wird im Rahmen dieser Arbeit auf dessen Messgenauigkeit untersucht.
- **Methode:** Dreißig gesunde Teilnehmer*innen wurden mit einem IMU auf Höhe der Lendenwirbelsäule ausgestattet und absolvierten drei maximale Sprints sowie drei Läufe in einem selbstgewählten Joggingtempo. Die Messstrecke von 60 m war Teil einer standardisierten 400 m Tartanbahn und es wurden die Parameter Geschwindigkeit, Schrittlänge und Schrittfrequenz erfasst. Als Referenzsystem diente ein optisches Lichtschrankenmesssystem. Zum Vergleich beider Systeme erfolgte die Bestimmung des Intraklassen-Korrelationskoeffizienten (ICC 2,1) sowie eine Bland-Altman-Analyse und eine regressions-basierte Bland-Altman-Analyse.
- **Ergebnisse:** Die Parameter Geschwindigkeit, Schrittlänge und Schrittfrequenz zeigten für beide Laufbedingungen eine hohe relative Messübereinstimmung im Vergleich zum optischen Lichtschrankensystem (ICCs 0.745-0.996). Die Bland-Altman-Analyse wies hohe Messdifferenzen durch zufällige- und systematische Fehler für Geschwindigkeit, Schrittlänge und Schrittfrequenz auf. Die regressionsbasierte Bland-Altman-Analyse zeigte mit zunehmender Schrittlänge einen systematischen Anstieg des Bias.
- **Diskussion:** Auf Grund hoher relativer Reliabilität, basierend auf den ICCs, und zugleich starken systematischen- und zufälligen Fehlern, zeigt das getestete System im Vergleich zum optischen Lichtschrankensystem divergierende absolute und relative Messübereinstimmungen. Entsprechend sind für die Nutzung dieses IMU-basierten Magnetschrankensystems in Sport und Wissenschaft weitere Untersuchungen zur Reliabilität und Validität für längere Strecken sowie zur Messung und Kalkulation der Schrittlänge erforderlich.

KEY WORDS:
IMU, Running, Cadence, Step Length, Biomechanics

SCHLÜSSELWÖRTER:
IMU, Laufen, Schrittfrequenz, Schrittlänge, Biomechanik

1. UNIVERSITY OF HAMBURG, *Department of Sports and Exercise Medicine, Institute of Human Movement Science, Hamburg, Germany*
2. FRIEDRICH SCHILLER UNIVERSITY JENA, *Department of Sports Science, Jena, Germany*
3. HELIOS ALBERT-SCHWEITZER-HOSPITAL, *Department of Cardiology, Internal Medicine I, Northeim, Germany*
4. HARVARD MEDICAL SCHOOL, *Department of Physical Medicine and Rehabilitation, Spaulding National Running Center, Cambridge, Massachusetts, USA*

CORRESPONDING ADDRESS:
Karsten Hollander, M.D., Ph.D.
Spaulding National Running Center
Harvard Medical School
1575 Cambridge St
Cambridge, Massachusetts, USA
: karsten.hollander@uni-hamburg.de

Introduction

Computerized analysis systems for human running biomechanics are predominantly available in specialized institutions or laboratories. They often consist of sensitive technology, operating complexity, and limited access (10). In contrast, inertial measurement units (IMU) are characterized by a small sensor device, which is commercially available, wearable, robust and able to register static posture and dynamic movements (9, 22). Due to these advantages and less complexity compared to laboratory systems, such as marker and camera-based 3D motion capture systems, IMUs have become a more frequently used sports technology (12, 18, 28). This provides running gait analysis under real-life conditions in the athletes natural training court and habitual environment (16, 19, 25, 29). An IMU system for in-field use is

Table 1

Mean values±SD for running speed, step length and cadence. HSTI=Humotion SmarTracks Integrated System; OJN=Opto Jump Next.

	HSTI	OJN
Running speed in m/s		
Jogging	3.76±0.69	3.77±0.65
Sprinting	6.74±1.04	6.81±1.03
Step length in m		
Jogging	1.41±0.26	1.31±0.20
Sprinting	1.96±0.36	1.73±0.21
Cadence in [steps^{-1}]		
Jogging	2.66±0.13	2.81±0.13
Sprinting	3.44±0.53	3.80±0.32

the Humotion SmarTracks Integrated System (HSTI). It consists of a mobile IMU system, worn by the athlete and an in-ground magnetic timing gate system placed beneath a running track. While the HSTI system demonstrates great potential for coaches, athletes and researchers, knowledge of the accuracy of HSTI is currently uncertain. In terms of previous in-field running studies, varying IMU-types and –technologies, as well as different data collection methods and sensor placements have been used, and showed varying validity for biomechancial running parameters (3, 16, 25, 29, 30). To our knowledge, no study has examined the validity of HSTI to date. Thus, the aim of our study was to evaluate the validity of the HSTI. We examined the systems accuracy for assessing spatio-temporal running gait parameters such as running speed, step length, and cadence during jogging in a self-selected speed and fast sprinting on a 60 m tartan track.

Methods

Study Design

A cross-sectional study design was used. The study reports according to the STRAD guidelines for reporting of diagnostic accuracy (6). Participants ran in their own footwear. As a reference system the photoelectric cell system Opto Jump Next (OJN, Microgate, Bolzano, Italy) was used (1, 13, 27).

Setting

The study took place on the universities´ standardized 400 m tartan athletic track. This track features an in-ground magnetic timing gate system, Humotion SmarTracks Integrated (HSTI). The data collection took place on two consecutive days in August 2016. No data were collected in case of rain in order to ensure the correct application of the reference system OJN, as well as to provide the same measurement conditions for all participants.

Participants and Experimental Protocol

Participants were recruited from staff and students of the university (age 23 to 37 years). The participants running background and experiences ranged between recreational and elite runners. Inclusion criteria were no musculoskeletal injuries, no operations six months prior to the study and no acute and chronic cardiovascular diseases. Research methods were approved by the local ethics committee (ID 47). Prior to the measurement, all participants gave informed written consent and were introduced to the measurement procedure. Then, the participants' anthropometric data was assessed (body mass, body height, and age). After this, a short warm-up in form of a run at a self-selected running speed was performed along the 400 m tartan track. For data collection with the HSTI system, participants were equipped with the Humotion waist belt, which involved the integrated sensor system. A measurement section of 60 m on the straight part of the 400 m track was chosen to assess the running gait parameters during jogging in a self-selected speed and sprinting conditions. The comparison system OJN covered a distance of 20 m. Due to this, the running section of 60 m was splitted into measurement sections of 0-20 m, 20-40 m and 40-60 m. To capture complete 60 m jogging and sprinting data, starting points were set at 40 m and 20 m before the OJN measurement section, as well as at the beginning of the OJN measurement section. For each trial, a running distance of 60 m was completed. To ensure comparable speed along the entire measurement section, participants began running one meter before the starting line and ended one meter after the finish line. Furthermore, participants were instructed to perform 6 trials, which included three jogging- and three sprinting runs. The participants running protocol was in a specified order: one jogging- and one sprinting trial per measurement section, whereas each participant started with jogging. In terms of recovery time, participants were instructed to walk the way back to the starting line after each run, and if needed, a self-selected break period could be taken. The break period ranged between two and five minutes. The measurement setup is displayed in figure 1.

Data Measurement and Variables

For creating a magnetic timing gate, two single bars with a length of 60 cm and a diameter of 2.5 cm, respectively, were arranged 1.22 m apart and in parallel to each other, which results in a width of a single standard athlete track lane. The arrangement of the magnetic timing gates was every 10 m along the measurement section. The IMU contained a 3D acceleration sensor, 400Hz, 16 g; 3D rotation rate sensor, 400Hz, 2000 deg/s; a 3D magnetic field sensor, 100Hz; and a battery (480 mAh). The IMU-size was 130x32x9mm, IMU-weight was 31g. The weight of the belt was 170 g. To allow a firm fit of the IMU and a free movement during running, the sensor system was placed between third and fifth lumbar vertebrae – as recommended by the company. In terms of the refenrence method OJN, the transmitting and receiving bars were placed parallel to one another with a distance of 1.22 m. OJN sampled data at 1000Hz. During testing, HSTI and OJN collected data simultaneously on the same track. Afterwards, the data was transmitted to a computer (Windows 7, Service Pack 1, 64 bit, 2.3 GHz, 8 GB RAM, Opto Jump Version 1.10.19.0; Windows 7, Service Pack 1, 64 bit, 2.6 GHz, 16 GB RAM, Humotion SmarTracks Diagnostics Version 3.4.701). Running speed, step length and cadence were measured. Step length was defined as foot contact to foot contact of the contralateral foot and cadence as steps per minute. In terms of HSTI measurements, all parameters were measured by the algorithm of the sensor system and no corrections were used. Furthermore, mean values for the measurement section of 20 m for all parameters were used.

Statistical Methods and Study Size

We calculated the mean values ± standard deviation (SD) of the HSTI data and OJN data for running conditions, subsections and parameter. To investigate the validity of HSTI compared to OJN, we calculated the intraclass correlation coefficients (ICC 2,1; relative reliability) as well as the bias (systematic error) and

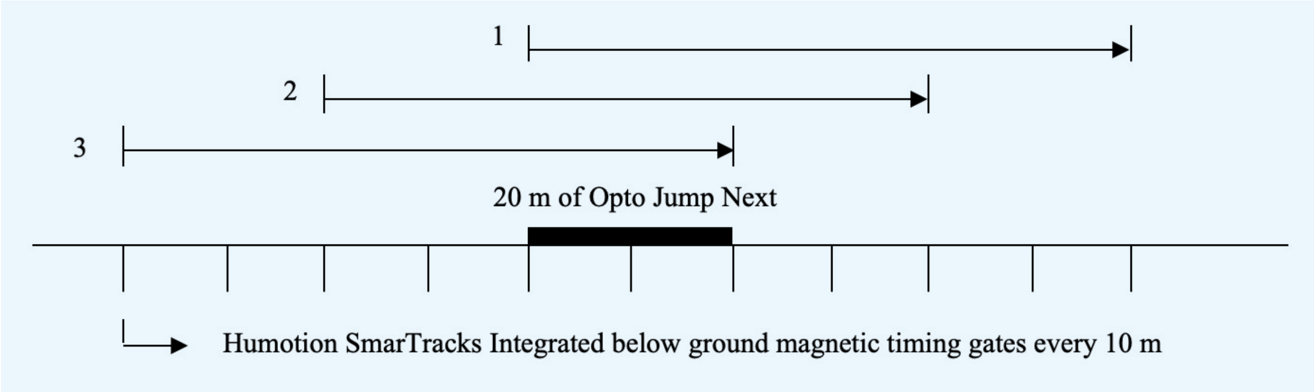

Figure 1

Measurement setup for HSTI and OJN: 1=starting point at the beginning of OJN, measurement section 0-20 m; 2=starting point 20 m before OJN, measurement section 20-40 m; 3=starting point 40 m before OJN, measurement section 40- 60 m; participants started one meter before the starting line and ended one meter after the finish line.

limits of agreement (random error) of the Bland-Altman plots (absolut reliability) (4). According to the results (e.g. fig. 1), the bias was not constant. Therefore, we also calculated the regression-based LoA (5). For interpreting the ICC (2,1; consistency), we used the following benchmarks: <0.00 poor agreement, 0.00-0.20 slight, 0.21-0.40 fair, 0.41-0.60 moderate, 0.61-0.80 substantial and >0.81 almost perfect (20). The calculations were done using SPSS (version 23).

Results

Participants

Ten female and 20 male subjects participated. Two from the 30 participants were excluded from data analyses: one drop-out occurred due to a retrospectively detected missing initialization of one IMU; the second drop-out occurred due to a loose fit of one participants waist belt during running, which generated not usable sensor outcomes. Thus, running trials of 28 participants (10 female, 18 male) were included into the analyses (mean ± SD: age 28.2±3.8 years, height 175.5±9.5 cm, body mass 70.6±10.7 kg, BMI 22.7±2.3 kg/m2). The collected data of 6 running trials per participant resulted in a total of 168 trials. While technical errors resulted in missing values, 155 trials out of 168 were included in the statistical analysis. The mean values ±SD for running speed, step length and cadence are shown in table 1.

Outcome Data and Main Results

Based on the ICC values (0.745 to 0.996, table 2), HSTI and OJN demonstrate substantial to almost perfect measurement agreement. Highest measurement agreement is shown for running speed (jogging: ICC [2,1] 0.932 to 0.971, 95% CI 0.854 to 0.997; sprinting: ICC [2,1] 0.814 to 0.996, 95% CI: 0.638 to 0.998). Also substantial to almost perfect measurement agreement is demonstrated for step length (jogging: ICC [2,1] 0.896 to 0.944, 95% CI: 0.789 to 0.976; sprinting: ICC [2,1] 0.785 to 0.845, 95% CI: 0.577 to 0.928) and cadence (jogging: ICC [2,1] 0.745 to 0.891, 95% CI: 0.480 to 0.948; sprinting: ICC [2,1] 0.900 to 0.938, 95% CI: 0.790 to 0.972). In terms of Bland-Altman analysis, bias for running speed, step length and cadence under the jogging condition were -0.037 to 0.029 m/s, 0.081 to 0.122 m and -0.198 to -0.086 s^{-1}, respectively. For sprinting, running speed, step length and cadence showed biases of -0.072 to -0.025 m/s, 0.115 to 0.284 m and -0.432 to -0.108 s^{-1}, respectively. Limits of agreement (LoA) ranged from -0.195 to 0.232 m/s for running speed, -0.142 to 0.304 m for step length and -0.346 to 0.028 s^{-1} for cadence during jogging. Within the sprinting condition, LoA ranged from -0.850 to 0.705 m/s for running speed, -0.071 to 0.623 m for step length and -0.796 to 0.101 s^{-1} for cadence. For step length and cadence an increase of biases from jogging to sprinting was demonstrated by the outcomes. Additionally, expressed by the LoA, an increase of random errors for all parameters from jogging to sprinting occured. These results are shown in table 2. Furthermore, regression-based Bland-Altman analysis indicated significant systematic effect for the bias of step length. The bias for the step length measurement increased with higher step length values. This effect is displayed in figure 2. Outcome data for regression analysis are shown in table 3.

Discussion

The purpose of the study was to determine the validity of the Humotion SmarTracks Intergrated system in reference to a photoelectric cell system. Our results indicate a substantial to almost perfect relative measurement agreement between both systems for jogging and sprinting conditions. However, both running conditions differed slightly regarding their ICCs. Compared to our findings for relative measurement agreement, outcomes for absolute measurement agreement demonstrated high systematic errors, and a high variability within the LoA was observed for all analysed parameters. These findings demonstrate increased absolute measurement differences between HSTI and OJN. In addition, systematic biases and random errors are higher for measuring running speed, step length and cadence during sprinting than during jogging. This trend demonstrates an increase in error values during higher running velocities and therefore indicates a slightly lower level of measurement agreement between HSTI and OJN. Furthermore, a systematic effect for bias of step length measurements was found, whereby bias for step length estimations increased with higher step length.

Two studies (17, 25) conducted IMU-based validation studies by measuring running speed. Hausswirth et al. (2009) tested a triaxial accelerometer against an infrared camera system during treadmill running at comparable velocities to those reported here. The authors reported a slightly better measurement accuracy, whereas we found comparable ICCs, but higher systematic differences. Parrington et al. (2016) tested a triaxial IMU against a laser speed gun during 100 m sprinting. In comparison to them, we found smaller systematic ›

Table 2

Outcome data for running gait parameters running speed, step length and cadence. RS=running speed in m/s; SL=step length in m; CAD=cadence in [s^{-1}]; measurement sections: S1 0-20m, S2 20-40m, S3 40-60m.

			ICC 2,1	CONFIDENCE INTERVAL		BIAS	LOA	LOWER LIMITS	UPPER LIMITS
Jogging	RS	S1	.971	0.937	0.986	0.029	0.203	-0.175	0.232
		S2	.932	0.854	0.969	-0.029	0.166	-0.195	0.137
		S3	.993	0.984	0.997	-0.037	0.147	-0.185	0.110
	SL	S1	.896	0.789	0.951	0.102	0.178	-0.077	0.280
		S2	.899	0.791	0.953	0.081	0.223	-0.142	0.304
		S3	.944	0.87	0.976	0.122	0.158	-0.036	0.280
	CAD	S1	.891	0.779	0.948	-0.086	0.114	-0.200	0.028
		S2	.857	0.712	0.932	-0.179	0.140	-0.319	-0.039
		S3	.745	0.48	0.886	-0.198	0.148	-0.346	-0.051
Sprinting	RS	S1	.814	0.638	0.91	-0.072	0.778	-0.850	0.705
		S2	.996	0.991	0.998	-0.025	0.186	-0.211	0.161
		S3	.889	0.775	0.947	-0.040	0.188	-0.228	0.148
	SL	S1	.785	0.577	0.898	0.115	0.186	-0.071	0.300
		S2	.832	0.661	0.921	0.264	0.262	0.002	0.526
		S3	.845	0.685	0.928	0.284	0.339	-0.055	0.623
	CAD	S1	.938	0.867	0.972	-0.108	0.209	-0.317	0.101
		S2	.909	0.808	0.958	-0.368	0.305	-0.673	-0.063
		S3	.900	0.79	0.954	-0.432	0.364	-0.796	-0.067

differences during sprinting, but still observed higher random errors. Especially our first measurement section (0-20 m) demonstrated a high magnitude of random errors and LoA, respectively, whereas the second and third split showed lower values. This variability could be related to the acceleration phase during sprinting (11, 25, 29). However, these findings have to be considered in terms of HSTI measurement accuracy. In reference to cadence estimations, the studies of Gouttebarge et al. (2015) and Wunsch et al. (2017) used IMUs during 400 m track running at comparable running speeds to those in our jogging condition. Both studies found comparable ICCs to our study but higher systematic differences were observed (16, 30). In addition, we found a critical magnitude of random errors. Hausswirth et al. (2009) also conducted cadence estimations and demonstrated better absolute and relative measurement agreement than those presented here. However, Hausswirth conducted their assessments on a treadmill where running gait movements are more regular and only of limited comparability to overground running (21, 31). For step length, Brahms et al. (2018), Wunsch et al. (2017) and Zrenner et al. (2018) analysed foot- and ankle-mounted IMU data during overground- and track running. In comparison to them, we found lower ICCs and a higher magnitude of observed differences (7, 30, 31). We also observed no constant bias for step length measurements. This indicates increasing systematic differences between both analysed systems with higher step length measurements. Whether this was caused by errors of the measurement system or is associated to the running speed, foot strike patterns, sensor placement or variations in running by the individuals needs to be addressed in future research (7, 24, 27, 29, 31). Furthermore, we found a nearly constant detection of higher step length and lower cadence for HSTI compared to OJN which probably can be attributed to a time lag between both measurement systems or might be caused by the lumbar sensor placement (23, 24). In terms of our lumbar sensor placement, previous works found a sensor placement at the foot or ankle more appropriate for investigations of running gait pattern, whereas lumbar placed sensors demonstrated to dampen sensor signals and provided less accurate gait pattern analysis, especially during higher running speeds (2, 24).

Table 3

Outcome data for regression analysis for step length measurements. Measurement section: S1: 0-20m, S2: 20-40m, S3: 40-60m

			B-VALUES	P-VALUES	LOA
Step length	Jogging	S1	0.349	.000	2.021
		S2	0.207	.019	2.062
		S3	0.239	.000	2.018
	Sprinting	S1	0.319	.020	2.045
		S2	0.329	.005	2.074
		S3	0.381	.008	2.111

When looking at the systematic effects and high variability for our outcome parameters, we found high error values for absolute measurements for HSTI compared to OJN. Accordingly, HSTI demonstrated less adequate measurements for spatio-temporal gait parameters compared to OJN. However, HSTI still offers potential for practical application during in-field training or competition by providing information regarding nearly real-time running characteristics. Future research is needed to analyse the HSTI during longer running distances as well as by using additional sensor placements.

There are a few relevant limitations to the study. First, OJN is an established and valid testing device for vertical jumps (8, 14) and spatio-temporal gait parameter (15) but has been rarely

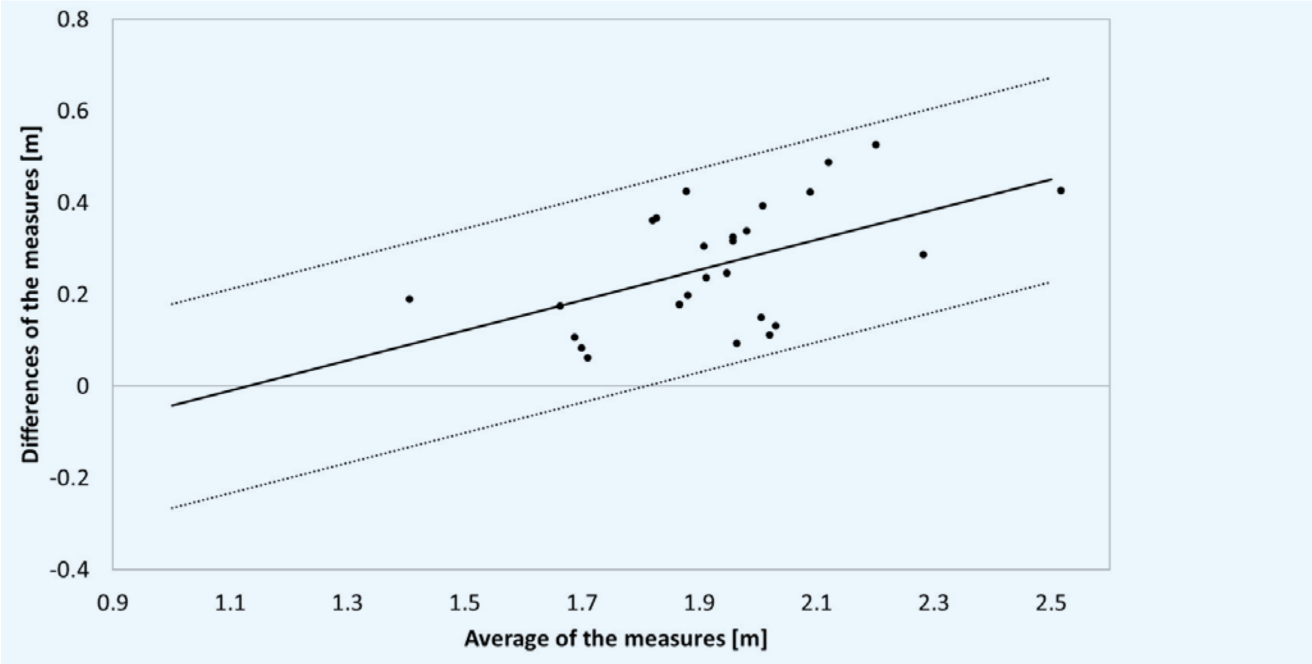

Figure 2

Regression-based Bland-Altman analysis obtained from HSTI and OJN measurements for step length during sprinting (running split 20-40 m). This plot demonstrates the systematic effect of an increasing bias with higher step length measurements.

used for spatio-temporal running gait analysis. Gindre et al. (2016) conducted a validation of OJN, and found high measurement accuracy for cadence at running speeds between 12.0 and 21.0 km/h. Further studies examined the accuracy of Opto Jump by measuring ground contact time and reported of acceptable to good validity (1, 26). Second, while good validity for OJN was found for cadence measurements, it is not known, if OJN influenced our measurements on step length and running speed, due to its position 3 mm from ground level (13, 26). Third, a firm fit of the waist belt with the integrated sensor system has to be secured to reduce additional movement of the sensors` running gait detection.

Conclusion

The IMU and magnetic timing gate system provides diverging measurement agreement compared to the reference system. Despite high relative measurement agreement (ICC), the absolut measurement agreement (bias and limits of agreements) demonstrate high error values. Therefore, caution must be taken for directly comparing values between both systems. In addition, attention should also be given for measuring step length. In terms of recommendation of HSTI in sports and research, further investigations regarding reliability and validity are needed. Future research should focus on step length calculations and alternative reference systems and sensor placements, as well as reliability and validity during longer running conditions.

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Conflict of Interest

The authors have no conflict of interest.

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