WIRELESS INSOLES TO MEASURE GROUND REACTION FORCES: STEP-BY-STEP VALIDITY IN HOPPING, WALKING, AND RUNNING

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This investigation assessed the validity of force measurements from wireless shoe insoles against a force plate and an instrumented treadmill. Thirteen subjects performed hopping tasks on a force plate and walked and ran on an instrumented treadmill while wearing the insoles. Ground reaction forces were measured with the two systems and analyzed per-step and per-hop to assess the accuracy and validity of the insoles. Peak force, contact time, and impulse were calculated for each step, and peak force for each hop. Across all measures, the insoles demonstrated high agreement with the force plate and the treadmill. Intraclass correlation coefficients ranged from 0.81-0.96. The wireless insoles appear to be a valid tool for ground reaction force measurement, and current results support the use of these devices for biomechanical studies outside the laboratory and in the field.

KEY WORDS: gait, measurement, step, biomechanics, validation.

INTRODUCTION: Measurement of the ground reaction and plantar forces experienced by an individual during running or walking is a common component of gait biomechanics investigations[1]. Understanding the magnitude and temporal nature of these forces can help characterize individual movement patterns and provide insights into performance characteristics and injury mechanisms. However, quantification of these forces has previously been limited to laboratory studies using force plates, instrumented treadmills, or wired insoles. Liberation of these measurements from the environmental and resource constraints of a laboratory would provide more rapid and representative data of running and walking activities in novel settings (Fong et al., 2008).

A wireless insole (Pedoped Insoles, Novel Gmbh, Munich, Germany) was recently developed to provide measurement of ground reaction forces during dynamic activities (Novel Gmbh, n.d.). The insoles measure the normal plantar force between the foot and the shoe at 100 Hz. Data are transmitted and recorded to a wireless device (e.g., iPod) via Bluetooth. Previous work examined other wired pressure-sensing insoles (e.g., Pedar insoles), but no work has been published validating the measurements of the wireless Pedoped insoles (Fong et al., 2008; Cordero et al. 2004; Mann et al. 2014). Furthermore, validation of other insoles has been limited to either single-step or average-value analysis (Abdul Razak et al. 2012). No models have been found that show step-by-step assessment of this type of tool over the course of an activity, which is relevant given the growing body of work analyzing inter-step variability during gait (Dingwell & Cusumano, 2010; Jordan & Newell, 2008).

Before researchers can take this new technology to the field, validity and reliability need to be established. This study tested the validity of the force measurements from the insoles against the measurements provided by a force plate and an instrumented treadmill. The insoles were tested in sport-relevant dynamic activities: hopping, walking, and running. The goals were to correlate force measurements of the insoles and the treadmill during walking and running and to determine if any consistent bias existed between the measurement systems. Further, the study tested the effect that sampling rate may have on the validity of dynamic force measurements of the wireless system by comparing the insole measurements at 100 Hz to that of a force plate at 1000 Hz during hopping. Finally, all analyses were done on a step-by-step basis to better understand the performance of the system over the duration of an activity.

METHODS: Thirteen subjects were recruited for the study (8 males, 5 females, 23.2±3.6 yr, 70.1±10.4 kg). Subjects were self-identified runners (taking part in ≥ 3 running sessions per week lasting ≥ 30 min) without current lower limb injury or use of orthotics. Upon arrival at the lab, each subject was weighed and instrumented with the Pedoped insoles that corresponded to his or her shoe size as well as the wireless data logging device (iPod Touch, Apple, Inc., Cupertino, USA). Subjects warmed up on the treadmill by jogging for 4 min with the insoles. After the warm-up period, the insoles were calibrated.

Each data collection consisted of 3 tasks: hopping, walking, and running. The hopping task involved the subject hopping on a force plate (AMTI AccuPower, Watertown, MA, USA) 10 times on his or her left foot and 10 times on his or her right foot. Peak force after contact was recorded at 1000 Hz from the force plate and 100 Hz from the insoles. The walking task involved the subject walking for 5 min on an instrumented treadmill (h/p/cosmos Quasar, h/p/cosmos Sports and Medical Gmbh, Nussdorf-Traunstein, Germany) at 5 km/hr, where vertical ground reaction force was recorded at 100 Hz from both the treadmill and the insoles. The running task involved the subject running for 5 min on the instrumented treadmill at 10 km/hr, and vertical ground reaction force was recorded from both the treadmill and insoles at 100 Hz. Each subject repeated the protocol on two different days, separated by at least 24 hr.

From the hopping task, peak vertical force after contact from each of the hops was recorded. From the walking and running tasks, a custom processing script was written in R to perform a step-by-step analysis of each trial. The vertical ground reaction forces from both the treadmill and insoles were thus used to calculate peak force, contact time, and impulse for each of the subject’s steps during each trial. Two hundred consecutive steps were extracted for the left and right foot from each trial for analysis.

To assess the validity of the insoles compared to the force plate or treadmill, fixed-rater intraclass correlation coefficients, standard error of measurements, and minimal detectable changes were calculated for each outcome variable for the left and right feet. Intraclass correlations between the insoles and the force plate or treadmill were assessed on the following criteria: ICC < 0.75 as poor to moderate agreement; 0.75-0.89 as good agreement, and ICC ≥ 0.90 as excellent agreement (Portney & Watkins, 2000). Additionally, grand means and standard deviations of each measure were calculated, along with the mean measurement difference for each step or hop as an indicator of system bias. All data analyses were conducted in R 3.3.2 (R Foundation for Statistical Computing, Austria).

RESULTS: For the hopping task, a total of 520 hops on the left and right feet across subjects was analyzed. The peak ground reaction forces during hopping had an average intraclass correlation of 0.96 between the force plate and the insoles across the two feet, demonstrating excellent agreement (Table 1).

Table 1
Validity of Wireless Insoles in Hopping

		Left Foot Force Plate vs. Insole N = 260 hops	Right Foot Force Plate vs. Insole N = 260 hops
Hopping	**Ground Reaction Force**		
	Grand Mean ± SD	1515.2 ± 366.0 N	1510.3 ± 377.5 N
	ICC (95% CI)	*0.95* (0.93, 0.96)	*0.96* (0.95, 0.97)
	Mean Bias (95% CI)	-5.5 N (-20.3, 9.30)	-25.1 N (-38.2, -12.0)
	SEM	81.9 N	84.4 N
	MDC	226.9 N	234.0 N

Data are presented as mean ± SD, intraclass correlation coefficient (95% CI), mean bias as within-step difference of force plate – insole measure (95% CI), standard error of the measurement (SEM), and minimal detectable change (MDC)

For both the walking and running tasks, 200 steps were extracted from each trial from each subject, yielding a total of 10,400 steps to be analyzed. Peak ground reaction forces had average intraclass correlations of 0.82 and 0.92 during walking and running, respectively. The temporal measures of contact time and impulse showed similar agreement, with average measures of 0.96 and 0.85 for contact time during walking and running, and 0.94 and 0.87 for the impulse during walking and running, respectively (Table 2).

Table 2
Validity of Wireless Insoles in Walking and Running

		Left Foot Treadmill vs. Insole N = 5200 steps	Right Foot Treadmill vs. Insole N = 5200 steps
Walking 5 km/hr	**Ground Reaction Force**		
	Grand Mean ± SD	789.3 ± 110.2 N	785.4 ± 123.9 N
	ICC (95% CI)	*0.81* (0.80, 0.82)	*0.83* (0.82, 0.84)
	Mean Bias (95% CI)	61.3 N (59.6, 63.1)	27.0 N (25.0, 29.0)
	SEM	48.1 N	51.1 N
	MDC	133.2 N	141.2 N
	Contact Time		
	Grand Mean ± SD	0.63 ± 0.03 s	0.63 ± 0.03 s
	ICC (95% CI)	*0.96* (0.96, 0.96)	*0.96* (0.96, 0.96)
	Mean Bias (95% CI)	0.00 (0.00, 0.00)	0.00 (0.00)
	SEM	0.01 s	0.01
	MDC	0.02 s	0.02
	Impulse		
	Grand Mean ± SD	348.5 ± 52.7 Nm	349.6 ± 58.0 Nm
	ICC (95% CI)	*0.94* (0.94, 0.94)	*0.93* (0.92, 0.93)
	Mean Bias (95% CI)	32.1 N-m (31.6, 32.6)	18.9 N-m (18.3, 19.5)
	SEM	13.9 Nm	15.3 Nm
	MDC	38.6 Nm	42.5 Nm
Running 10 km/hr	**Ground Reaction Force**		
	Grand Mean ± SD	1429 ± 243.3 N	1438.8 ± 244.4 N
	ICC (95% CI)	*0.93* (0.92, 0.93)	*0.90* (0.89, 0.90)
	Mean Bias (95% CI)	209.7 N (207.3, 211.9)	147.0 N (144.1, 149.9)
	SEM	64.4 N	77.3 N
	MDC	178.4 N	214.3 N
	Contact Time		
	Grand Mean ± SD	0.26 ± 0.02 s	0.26 ± 0.02 s
	ICC (95% CI)	*0.83* (0.82, 0.84)	*0.86* (0.85, 0.87)
	Mean Bias (95% CI)	0.02 s (0.02, 0.02)	0.02 s (0.02, 0.02)
	SEM	0.01 s	0.01 s
	MDC	0.02 s	0.02 s
	Impulse		
	Grand Mean ± SD	222.5 ± 40.3 Ns	226.0 ± 41.1 Nm
	ICC (95% CI)	*0.89* (0.88, 0.90)	*0.85* (0.85, 0.86)
	Mean Bias (95% CI)	47.4 Ns (47.0, 47.9)	40.9 Nm (40.4, 41.4)
	SEM	13.4 Ns	15.9 Nm
	MDC	37.0 Ns	44.2 Nm

Data are presented as mean ± SD, intraclass correlation coefficient (95% CI),), mean bias as within-step difference of treadmill – insole measure (95% CI) , standard error of the measurement (SEM), and minimal detectable change (MDC)

DISCUSSION: The Pedoped wireless insoles, as a system for measuring plantar force parameters, agreed with the measurements from a force plate and an instrumented treadmill in the dynamic activities of hopping, running, and walking. Across all outcome variables, the wireless insoles had good-to-excellent correlations with the gold standard system against which it was being compared. Peak vertical ground reaction forces had average intraclass correlations of 0.96, 0.82, and 0.92 across the hopping, walking, and running. The temporal measures of contact time and impulse showed similarly good agreement, with average walking and running measures of 0.96 and 0.85 for contact time and 0.94 and 0.87 for the impulse, respectively.

Apart from demonstrating generally good-to-excellent agreement between the wireless insoles and established measurement systems, this study provides additional important information for biomechanics investigators. First, the lower sampling rate of the insoles relative to the force plate did not adversely affect its performance in measuring impact, as agreement with the force plate was excellent. With the mobilization of new measurement tools often being limited by processing capability, this can give researchers confidence that systems may not need the computationally-intensive higher sampling rates of 500 or 1000 Hz for certain running and jumping tasks. An avenue for further exploration would be to sub-sample the force plate's data at 100 Hz to verify the correlation. Observations of the force plate's signal around the impact peaks are consistent with the correlations being robust to this sub-sampling, as the force generally did not rapidly decay on either 5 ms window above or below the peak. Secondly, the treadmill measures demonstrated slightly more variance against the wireless insoles as compared to the excellent agreement observed with the force plate. The average ICC of the ground reaction forces were found to be 0.82 and 0.92 in walking and running, respectively, on the treadmill compared to 0.96 in hopping on the force plate. That supports previous work, which indicated a greater error in ground reaction force measurements of instrumented treadmills compared to wired insoles (Van Alsenoy et al. 2016). However, that slight discrepancy may be due to the more complex dynamics of running and walking. These tasks introduce shearing forces, which could contribute to a greater variance in the measurement quality of the insoles. Finally, the step-by-step analysis employed here provided a more comprehensive profile of the performance of the measurement systems being examined. Previous work examining the validity and reliability of wired insoles for force measurement found varying levels of agreement but collapsed the results to trial averages or restricted collections to short durations (Castro et al., 2011; Van Alsenoy et al., 2016). That suggests that validity assessments of new tools can be improved by more granular analyses of the task at hand.

CONCLUSION: The Pedoped wireless insoles are a valid tool for measuring plantar forces and demonstrate excellent agreement with a force plate and good agreement with an instrumented treadmill. Furthermore, the 100 Hz sampling rate of the system was sufficient to capture the peak impact forces. The ease-of-use of a wireless plantar force measurement system can enable researchers to expand dynamic gait measurements into clinical or sport-specific environments. This system may facilitate the exploration of vertical ground reaction forces generated by athletes and patients alike in sport or task-specific environments and may provide novel insights into performance indicators or injury mechanisms outside the laboratory.

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