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Validation of Moticon's OpenGo sensor insoles during gait, jumps, balance and cross-country skiing specific imitation movements

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ABSTRACT

The purpose of this study was the experimental validation of the OpenGo sensor insole system compared to PedarX sensor insole and AMTI force-plate systems. Sixteen healthy participants performed trials in walking, running, jumping (drop and counter movement jumps), imitation drills and balance, with simultaneous measures of all three systems. Detected ground contact and flight times with OpenGo during walking, running and jumping were similar to those of AMTI. Force–time curves revealed comparable shapes between all three systems. Force impulses were 13–34% lower with OpenGo when compared to AMTI. Despite differences in mean values in some exercise modes, correlations towards AMTI were between $r = 0.8$ and $r = 1.0$ in most situations. During fast motions, with high force and impact, OpenGo provided lower force and latency in force kinetics. During balance tasks, discrepancy in the centre of pressure was found medio-lateral, while anterio–posterior direction was closer to AMTI. With awareness of these limitations, OpenGo can be applied in both clinical and research settings to evaluate temporal, force and balance parameters during different types of motion. The fully mobile OpenGo system allows for the easy and quick system application, analysis and feedback under complex field conditions, as well.

Introduction

Since the foot is typically the only body part interacting with the ground, quantitative information about foot kinetics and dynamics is critical in many research areas. The quantification of plantar forces is, therefore, a valuable method for the analysis of human body motion. There are two measurement concepts for obtaining such quantitative information: (1) stationary force plates and pressure mats and (2) wearable sensor insoles and socks.

In general, the flexibility of wearable devices has to be traded off against the accuracy of stationary systems. In this context, force plates represent the gold-standard method for determining gait events with high accuracy. However, the method is usually restricted to laboratory environments, with the number of force plates limiting the number of steps that can be recorded. Conversely, sensor insoles provide a practical outcome for collecting data in both laboratory and field settings (with almost no limitations in their application) and offer high efficiency, flexibility and mobility.

Based on the review of Razak, Zayegh, Begg, and Wahab (2012), typical applications of sensor insoles are sports performance analysis; footwear design; injury prevention; improvement in balance control; diagnosis of foot pathologies; human identification; monitoring posture allocation and rehabilitation support systems. In the past decade, increased attention was paid to the application of sensor insoles in outdoor sports such as cross-country skiing and alpine skiing (Andersson

et al., 2014; Holmberg, Lindinger, Stöggl, Björklund, & Müller, 2006; Lindinger, Göpfert, Stöggl, Müller, & Holmberg, 2009; Nakazato, Scheiber, & Müller, 2011; Scheiber, Seifert, & Müller, 2012; Stöggl, Bishop, Höök, Willis, & Holmberg, 2015; Stöggl, Björklund, & Holmberg, 2013; Stöggl & Holmberg, 2015; Stöggl, Kampel, Müller, & Lindinger, 2010; Stricker, Scheiber, Lindenhofer, & Müller, 2010). Based on this development, the establishment of accurate and efficient measurement devices is crucial.

One of the limitations of these portable systems is that sensor insoles measure pressure and the "normal" force, which is not necessarily similar to the vertical ground reaction force, is calculated (Kalpen & Seitz, 1994; Kernozek, LaMott, & Dancisak, 1996; McPoil, Cornwall, & Yamada, 1995).This characteristic should be taken into consideration in motions where considerable shear forces are acting on the insoles (e.g., sideward skating push-off, back–forth steps), which might be under-represented when using sensor insoles.

There are several studies about the repeatability and validity of sensor insoles (Gurney, Kersting, & Rosenbaum, 2008; Healy, Burgess-Walker, Naemi, & Chockalingam, 2012; Hurkmans et al., 2006; Martínez-Nova, Cuevas-García, Pascual-Huerta, & Sánchez-Rodríguez, 2007; Putti, Arnold, Cochrane, & Abboud, 2007; Ramanathan, Kiran, Arnold, Wang, & Abboud, 2010). However, the shortcoming of these studies is that they exclusively analysed walking and running tasks. Accuracy and repeatability measures during jumping and balance tasks and

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special motions provoking shear forces on the insoles were not considered during their research. The Pedar® mobile system (Novel GmbH, Munich, Germany), one of the most commonly used and well-established systems for in-shoe pressure measurements, was shown to be repeatable and valid (e.g., +Hurkmans et al., 2006; Putti et al., 2007), and as such is considered to be the gold standard among sensor insole systems.

Recently, OpenGo, a novel wearable device for measuring the plantar pressure distribution and the acceleration of the foot was launched by Moticon GmbH, Germany. The OpenGo system consists of a completely wireless sensor insole, with an integrated internal storage, which can be used in virtually any shoe. It is commercially available and may provide a new manner of carrying out human motion research by releasing test participants from the shortcomings of cables and additional devices for data storage – a necessity proposed also by Razak et al. (2012). Furthermore, the system brings analysis methods into the field and daily life, which up to now have been restricted to in-lab use.

The present paper provides a thorough experimental validation of the OpenGo sensor insole measurement system compared to the AMTI force plate system and the gold-standard sensor insole system, PedarX. The major aim was to quantitatively assess the accuracy of the system during walking, running, jumping, body balance and special imitation motions specific to cross-country skiing – all of which are movements relevant for a wide range of application areas in sports and in public health.

Methods

Participants

Sixteen participants (2 females, 14 males; age 31 ± 10 years old; body height 1.80 ± 0.08 m; body mass 77 ± 11 kg) volunteered to take part in this study. The participants were all sport science students, familiar with the tested movements. The study was approved by the Institutional Review Board, and participants were informed in detail about the testing procedures, as well as possible benefits and risks of the investigation prior to signing an institutionally approved informed consent to participate in the study.

### General design of the study

The experiment consisted of four different measurement trials during: (1) slow walking, fast walking and running at a self-selected speed; (2) standing still, counter movement jumps and drop jumps; (3) three different imitation drills and (4) two balance tests.

Instruments

During each trial, forces were recorded simultaneously using an AMTI force plate (AMTI BP600900, Advanced Mechanical Technology Inc., Watertown, MA), the PedarX Mobile System (Novel GmbH, Munich, Germany) and the OpenGo (Moticon GmbH, Munich, Germany) sensor insoles. The 6-component

AMTI force plate was placed flush with the floor in the centre of a 15-m walkway sampling at 1000 Hz. Plantar forces were recorded at 50 Hz by the PedarX mobile system (Novel GmbH, Munich, Germany) consisting of two insoles (containing 99 capacitive sensors each) that measured pressure distribution, a data logger with an internal flash memory (32 MB), and cable sets. The insoles were calibrated with a computerised PedarX device, utilising homogenous air pressure.

The OpenGo system consists of two sensor insoles (containing 13 capacitive sensors each, Figure 1) that measure the plantar pressure distribution and the acceleration in three dimensions in space. Based on the specifications of Moticon, the maximum recording capacity of the sensor insole is 5:48 h at a sample rate of 50 Hz for all sensors. Each sensor insole electronically incorporates a 3-dimensional MEMS accelerometer (Bosch Sensortech BMA150), which is located in the insole centre. In the current study, the g-range was set to ±8g for all three axes. The Z-axis points to the normal direction with reference to the ground plane, the Y-axis is in the line of walking and the X-axis is in medial/lateral direction. The plantar forces were computed from the pressure distribution at 50 Hz. Each sensor insole incorporates a processing unit, memory (16 MB flash memory each) and a wireless module that is used for data transmission and for controlling the sensor insole. No external devices or cables are needed to operate the system. The OpenGo sensor insoles are factory calibrated with homogeneously distributed loads, covering
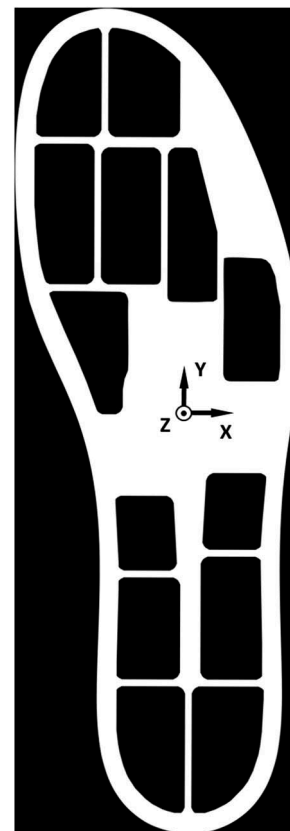
Figure 1. Layout of the capacitive pressure sensors. The white keep-out areas are due to technical restrictions. For the 3-dimensional accelerometer the Z-axis points to the normal direction with reference to the ground plane, the Y-axis is in the line of walking and the X-axis is in medial/lateral direction.

the specified load range from 0 to 40 N · cm^{-2}. Moticon furthermore states that no further calibration is needed within the specified lifetime of 100-km running; hence, no update calibration was performed for the purpose of the present study.

Participants were requested to wear appropriately sized standardised neutral running shoes (Adidas Supernova) with the OpenGo insoles and PedarX insoles sandwiched between the foot and the inside of the shoe. The custom insole of the shoe was removed, with the OpenGo insoles placed first, followed by the PedarX insoles. Sensor insoles were placed in both the left and right shoes. Synchronisation between all three systems was done by performing two stamps with one leg on the AMTI force plate at the beginning and end of each trial.

Experimental situations

The four sessions were recorded separately and consisted of: (1) four trials, each with slow walking, fast walking and running at a self-selected speed on the 15-m walkway; (2) 10 s standing still for weight measurements, followed by four counter movement jumps and four drop jumps from a 30-cm platform; (3) 20-s single leg stance (static balance) followed by the Y-Excursion Balance test (dynamic balance) and (4) imitation drills with a special focus on motions specific to cross-country skiing and targeting the evolution of force components within the insole plane (acting as shear forces on the sensor insoles). Four trials in each of the following situations were performed: single leg jumps back and forth on the force plate (Figure 2(A)); single leg jump on the force plate with the goal of achieving maximal horizontal jump distance (diagonal stride motion (Figure 2(B)); and sideways single leg jump on the force plate and back again (skating imitation, Figure 2(C)).

Kinematic variables

For kinetics, the impulse of force, maximal force and mean force were calculated. During gait, the first maxima, the force minima at ~50% of ground contact and the second maxima were detected (Figure 3(A) & 3(B)). Kinematic data, as ground

contact time, time to peak force, swing time, flight time and so on, was determined from force data. Furthermore, for the OpenGo system to improve detection of ground contact time during walking, running and jumping, the internal accelerometers were combined with the pressure data. To do so, in a first step, a force threshold was applied on the total force value to roughly detect heel-strike and toe-off during walking and running. Within a window of 100 ms around these time points, the algorithm used the local minima in the sequence of unfiltered acceleration values in Y-direction (anterio-posterior) to fine-tune the detection time points. A comparable detection algorithm was used for analysing jumps, where the flight time and the ground contact time were detected using the acceleration data in Z-direction in combination with the force data. For the time point of jump-off, the algorithm determined the time point of minimum acceleration in Z-direction. For the instant of landing, the algorithm determined the first increase of the acceleration in Z-direction by at least $0.5g$ within a window of 100 ms around the rough landing point. For the balance tasks, the mean force, force maxima and force minima were detected. Furthermore, the centre of pressure (COP) was evaluated by calculating the maximal amplitude (from minima to maxima), the standard deviation across the trial and the path length, all separately for medio-lateral and anterio-posterior directions. The processing of data was managed using IKE-master software (IKE-Software Solutions, Salzburg, Austria) and MS Excel 2010 (Microsoft Corporation, Redmond, Washington, USA).

Statistical analysis

Except for the two balance tests where only one trial was performed, the mean values from the four trials in each measurement situation were calculated and used in the statistical analyses. All dependent variables were checked for normality using the Shapiro–Wilk test. One way repeated measure ANOVAs were conducted to test for differences between the three measurement systems. Pearson's product-moment correlation coefficient was calculated to assess the relative agreement between the systems. Furthermore, mean bias between the systems and 95% limits of agreement (LoA) (Bland &
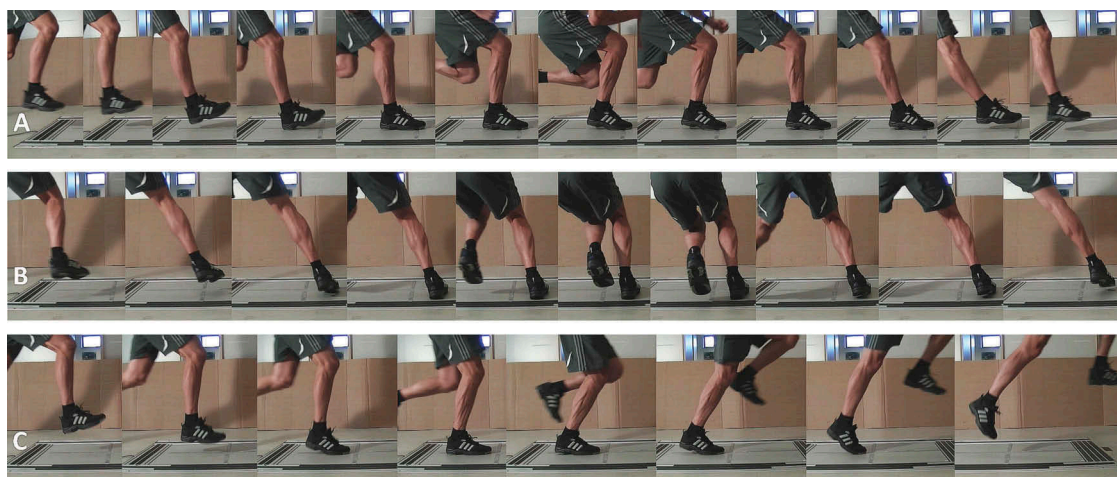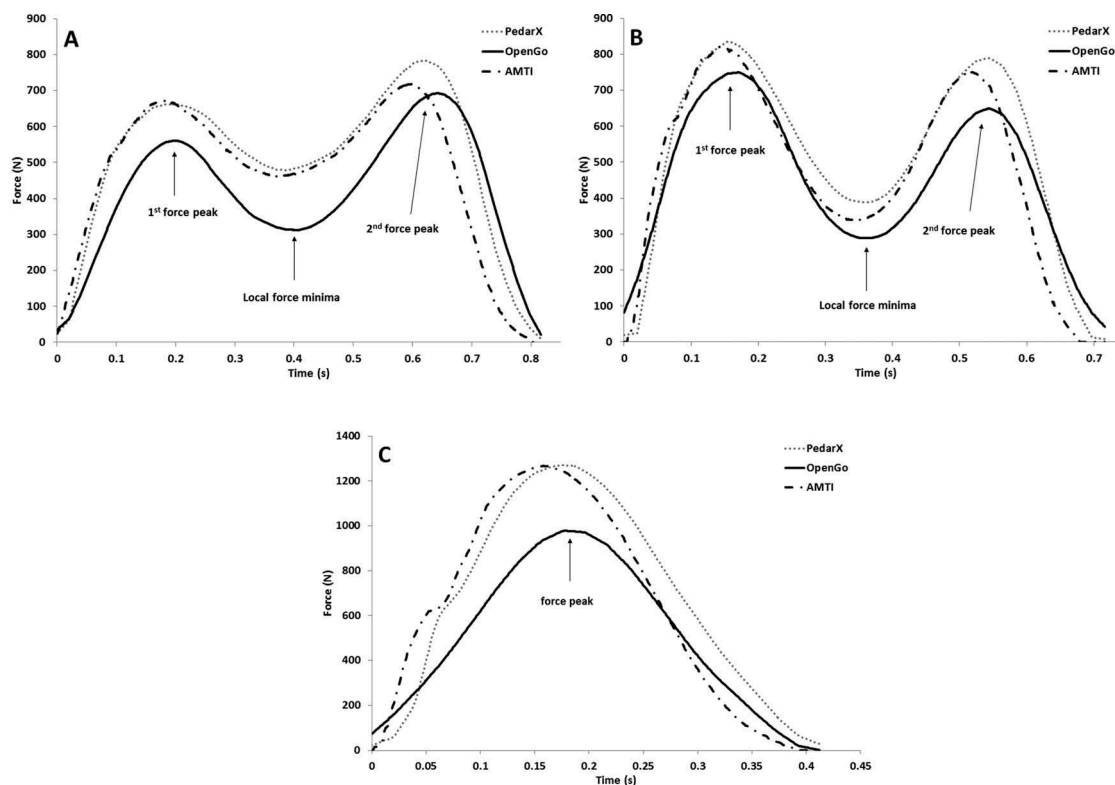

Figure 2. Picture series of the special imitation motions (A) single leg jumping back and forth on the force plate, (B) single leg jump on the force plate with the goal of achieving maximal horizontal jump distance (diagonal stride motion), and (C) sideways single leg jumping on the force plate and back again (skating imitation).

Figure 3. Time course of the total forces recorded by the AMTI force plate, the PedarX and OpenGo sensor insole systems during the ground contact phase of one representative participant during slow walking (A), fast walking (B) and running (C). The data represents the mean of four time-normalised cycles.

Altman, 1986) in absolute and in percent of the grouped mean were calculated. Heteroscedasticity was examined by calculating the correlation coefficient between the absolute difference and the individual means (Atkinson & Nevill, 1998; Bland & Altman, 1986). The alpha level of significance was set at 5%.

Results

Tables 1–4 present the means ± SDs for each method and each type of exercise, and the mean bias (d) and 95% LoA between the three systems.

Table 1. Comparison of kinetic and kinematic variables during slow walking, fast walking and running between the AMTI force plate, PedarX and OpenGo.

	Mean ± SD			Bias (%)			95% limits of agreement (% grouped mean)		
	AMTI	PedarX	OpenGo	OpenGo vs. AMTI	PedarX vs. AMTI	OpenGo vs. PedarX	OpenGo vs. AMTI	PedarX vs. AMTI	OpenGo vs. PedarX
Slow Walking									
GCT (s)	0.77 ± 0.06[†]	0.78 ± 0.05[†]	0.76 ± 0.05[†]	−0.01 (−1%)	0.01 (2%)	−0.02 (−3%)	−0.02 (3%)	0.01 (2%)	0.03 (4%)
Impulse (Ns)	493 ± 87[†]	537 ± 75[†]	376 ± 64[†]	−118 (−24%)	44 (9%)	−162 (−30%)	86 (20%)	81 (16%)	53 (12%)
F_{peak1} (N)	893 ± 161	892 ± 140	583 ± 75[†]	−310 (−35%)	−2 (0%)	−308 (−35%)	253 (34%)	151 (17%)	200 (27%)
F_{min} (N)	570 ± 107[†]	622 ± 95[†]	356 ± 75[†]	−214 (−38%)	52 (9%)	−266 (−43%)	89 (19%)	89 (15%)	75 (15%)
F_{peak2} (N)	846 ± 123[†]	928 ± 120[†]	689 ± 112[†]	−157 (−19%)	82 (10%)	−239 (−26%)	147 (19%)	167 (19%)	138 (17%)
t_{Fpeak1} (s)	0.17 ± 0.02[†]	0.18 ± 0.03[†]	0.20 ± 0.03[†]	0.04 (22%)	0.01 (9%)	0.02 (12%)	0.04 (21%)	0.03 (16%)	0.04 (20%)
t_{Fmin} (s)	0.35 ± 0.04	0.35 ± 0.05	0.38 ± 0.04	0.03 (8%)	0.00 (0%)	0.03 (9%)	0.08 (23%)	0.03 (9%)	0.10 (26%)
t_{Fpeak2} (s)	0.61 ± 0.04[†]	0.62 ± 0.04[†]	0.66 ± 0.05[†]	0.05 (8%)	0.01 (2%)	0.04 (6%)	0.04 (6%)	0.03 (5%)	0.05 (7%)
Fast Walking									
GCT (s)	0.61 ± 0.05[†]	0.62 ± 0.06[†]	0.60 ± 0.05[‡]	−0.01 (−1%)	0.02 (3%)	−0.02 (−4%)	−0.02 (3%)	0.02 (3%)	0.03 (5%)
Impulse (Ns)	395 ± 79[†]	434 ± 73[†]	291 ± 57[†]	−105 (−27%)	39 (10%)	−144 (−33%)	83 (24%)	71 (17%)	56 (15%)
F_{peak1} (N)	1082 ± 168[†]	950 ± 123[†]	602 ± 55[†]	−481 (−44%)	−132 (−12%)	−349 (−37%)	309 (37%)	188 (18%)	219 (28%)
F_{min} (N)	425 ± 117[†]	483 ± 116[†]	276 ± 83[†]	−148 (−35%)	59 (14%)	−207 (−43%)	93 (26%)	86 (19%)	105 (28%)
F_{peak2} (N)	856 ± 141[†]	944 ± 152[†]	673 ± 148[†]	−183 (−21%)	88 (10%)	−271 (−29%)	122 (16%)	172 (19%)	131 (16%)
t_{Fpeak1} (s)	0.13 ± 0.02[†]	0.14 ± 0.02[†]	0.17 ± 0.03[†]	0.04 (29%)	0.01 (7%)	0.03 (21%)	0.06 (41%)	0.02 (13%)	0.06 (37%)
t_{Fmin} (s)	0.31 ± 0.03	0.32 ± 0.03	0.34 ± 0.04[$]	0.02 (8%)	0.01 (2%)	0.02 (6%)	0.05 (16%)	0.02 (7%)	0.06 (18%)
t_{Fpeak2} (s)	0.48 ± 0.05[†]	0.49 ± 0.06[†]	0.52 ± 0.07[†]	0.05 (10%)	0.02 (3%)	0.03 (6%)	0.05 (11%)	0.01 (3%)	0.05 (10%)
Running									
GCT (s)	0.34 ± 0.04[†]	0.37 ± 0.04[†]	0.33 ± 0.04[‡]	−0.01 (−2%)	0.03 (8%)	−0.04 (−10%)	0.04 (12%)	0.03 (8%)	0.04 (12%)
Impulse (Ns)	317 ± 49	333 ± 42	218 ± 24[†]	−99 (−31%)	16 (5%)	−115 (−34%)	77 (29%)	55 (17%)	57 (21%)
F_{max} (N)	1701 ± 366	1715 ± 294	1058 ± 122[†]	−643 (−38%)	13 (1%)	−656 (−38%)	566 (41%)	257 (15%)	428 (31%)
t_{Fmax} (s)	0.14 ± 0.02	0.14 ± 0.02	0.19 ± 0.04[†]	0.06 (44%)	0.00 (3%)	0.05 (39%)	0.02 (31%)	0.02 (13%)	0.05 (29%)

GCT, ground contact time; F_{peak1}, first force peak during ground contact; F_{min}, local force minima at approximately 50% of ground contact; F_{peak2}, second force peak during ground contact; t_{Fpeak1}, time to first force peak; [†]significantly different to the other two methods; [$]different to AMTI force plate; [‡] different to PedarX.

Table 2. Comparison of kinetic and kinematic variables during the two vertical jumps, counter movement jump (CMJ) and drop jump (DJ) between the AMTI force plate, PedarX and OpenGo.

	Mean ± SD			Bias (%)			95% limits of agreement (% grouped mean)		
	AMTI	PedarX	OpenGo	OpenGo vs. AMTI	PedarX vs. AMTI	OpenGo vs. PedarX	OpenGo vs. AMTI	PedarX vs. AMTI	OpenGo vs. PedarX
Weight (N)	773 ± 113	771 ± 109	616 ± 139[†]	−155 (−20%)	10 (0%)	−165 (−20%)	174 (25%)	191 (25%)	234 (33%)
Impulse CMJ (Ns)	941 ± 180	1013 ± 165[$]	821 ± 148[†]	−114 (−13%)	83 (8%)	−197 (−19%)	195 (22%)	197 (20%)	210 (23%)
F_{max} CMJ (N)	1726 ± 252	1880 ± 224[$]	1414 ± 271[†]	−303 (−18%)	170 (9%)	−473 (−25%)	308 (20%)	350 (19%)	327 (20%)
Time to F_{max} CMJ (s)	0.72 ± 0.21	0.71 ± 0.19	0.74 ± 0.21	0.01 (3%)	−0.01 (0%)	0.02 (4%)	0.16 (23%)	0.09 (13%)	0.14 (19%)
Flight time CMJ (s)	0.53 ± 0.07	0.49 ± 0.10[$]	0.53 ± 0.07[‡]	0.01 (1%)	−0.04 (−6%)	0.04 (8%)	0.03 (6%)	0.10 (20%)	0.10 (17%)
F_{max} landing CMJ (N)	4394 ± 1104	3047 ± 473[$]	1379 ± 200[†]	−3023 (−69%)	−1347 (−31%)	−1676 (−55%)	2086 (72%)	2272 (61%)	838 (37%)
Impulse DJ (Ns)	522 ± 111	553 ± 99	392 ± 79[†]	−126 (−25%)	36 (6%)	−162 (−29%)	147 (32%)	123 (23%)	122 (26%)
F_{max} DJ (N)	4667 ± 1002	3918 ± 678[$]	1897 ± 285[†]	−2678 (−59%)	−730 (−16%)	−1948 (−52%)	1845 (57%)	1414 (34%)	1250 (44%)
Time to F_{max} DJ (s)	0.06 ± 0.02	0.08 ± 0.02[$]	0.17 ± 0.03[†]	0.11 (176%)	0.02 (38%)	0.08 (100%)	0.04 (36%)	0.03 (39%)	0.04 (36%)
GCT DJ (s)	0.22 ± 0.05	0.25 ± 0.05	0.22 ± 0.05[†]	−0.01 (−2%)	0.02 (10%)	−0.03 (−11%)	0.02 (7%)	0.03 (13%)	0.03 (13%)
Flight time DJ (s)	0.49 ± 0.07	0.47 ± 0.08	0.50 ± 0.07[‡]	0.00 (1%)	−0–03 (−5%)	0.03 (7%)	0.02 (4%)	0.05 (9%)	0.04 (9%)

CMJ, counter movement jump; F_{max}, maximal force; DJ, drop jump; GCT, ground contact time; [†]significantly different to the other two methods; [$]different to AMTI force plate; [‡]different to PedarX.

Table 3. Comparison of kinetic and kinematic variables during balance testing between the AMTI force plate, PedarX and OpenGo.

	Mean ± SD			Bias (%)			95% limits of agreement (% grouped mean)		
	AMTI	PedarX	OpenGo	OpenGo vs. AMTI	PedarX vs. AMTI	OpenGo vs. PedarX	OpenGo vs. AMTI	PedarX vs. AMTI	OpenGo vs. PedarX
Single- Leg Balance									
F_{mean} (N)	751 ± 111	841 ± 104[$]	787 ± 145	51 (5%)	105 (12%)	−53 (−6%)	235 (30%)	244 (29%)	231 (27%)
F_{max} (N)	821 ± 122	923 ± 122[$]	962 ± 151[$]	153 (17%)	114 (12%)	39 (4%)	268 (48%)	255 (46%)	261 (36%)
F_{min} (N)	668 ± 144	713 ± 131	488 ± 141[†]	−168 (−27%)	62 (7%)	−230 (−32%)	217 (30%)	320 (31%)	217 (28%)
SD (N)	11.1 ± 9.9[†]	28.6 ± 8.9[†]	89.4 ± 23.9[†]	79 (708%)	16 (158%)	63 (213%)	49 (95%)	14 (71%)	46 (78%)
COP amplitude M-L (mm)	43.3 ± 9.5[†]	24.3 ± 4.4[†]	17.1 ± 4.8[†]	−26 (−60%)	−19 (−44%)	−7 (−30%)	15 (50%)	14 (40%)	5 (27%)
COP amplitude A-P (mm)	81.7 ± 27.8[†]	70.8 ± 26.0[$]	68.5 ± 26.2[$]	−11 (−16%)	−12 (−13%)	1 (−3%)	35 (48%)	15 (21%)	39 (58%)
COP SD M-L (mm)	8.5 ± 2.2[†]	4.9 ± 1.0[†]	3.6 ± 1.0[†]	−5 (−58%)	−4 (−42%)	−1 (−28%)	4 (67%)	3 (45%)	2 (46%)
COP SD A-P (mm)	14.2 ± 4.9	12.5 ± 4.5[$]	13.8 ± 6.9	0 (−3%)	−2 (−12%)	2 (10%)	8 (60%)	3 (22%)	9 (72%)
Path length M-L (mm)	1241 ± 390[†]	580 ± 146[†]	357 ± 130[†]	−912 (−71%)	−685 (−53%)	−227 (−38%)	606 (74%)	534 (57%)	219 (46%)
Path length A-P (mm)	1404 ± 704	1041 ± 410[$]	1243 ± 415	−150 (−11%)	−389 (−26%)	239 (19%)	1042 (78%)	666 (54%)	702 (61%)
Y-Excursion Test									
F_{mean} (N)	735 ± 113	837 ± 106[†]	752 ± 138	29 (2%)	117 (14%)	−87 (−10%)	237 (33%)	244 (28%)	197 (27%)
F_{max} (N)	865 ± 119	985 ± 84[$]	954 ± 169[$]	107 (10%)	134 (14%)	−27 (−3%)	297 (44%)	260 (32%)	261 (24%)
F_{min} (N)	614 ± 112[†]	684 ± 125[†]	472 ± 108[†]	−131 (−23%)	80 (11%)	−211 (−31%)	238 (32%)	209 (31%)	141 (25%)
SD (N)	36.3 ± 11.4[†]	52.5 ± 9.4[†]	105.1 ± 31.3[†]	72 (190%)	17 (45%)	55 (100%)	62 (86%)	25 (57%)	69 (87%)
COP amplitude M-L (mm)	51.8 ± 6.4[†]	29.9 ± 5.4[†]	21.0 ± 3.8[†]	−31 (−60%)	−22 (−42%)	−9 (−30%)	12 (33%)	12 (28%)	9 (34%)
COP amplitude A-P (mm)	106.9 ± 19.3[†]	90.5 ± 14.5[$]	85.7 ± 17.5[$]	−20 (−20%)	−18 (−15%)	−2 (−5%)	26 (26%)	17 (17%)	30 (33%)
COP SD M-L (mm)	11.6 ± 1.5[†]	7.0 ± 1.9[†]	4.7 ± 1.3[†]	−7 (−59%)	−5 (−40%)	−2 (−33%)	2 (23%)	2 (20%)	2 (38%)
COP SD A-P (mm)	23.0 ± 4.9[†]	19.6 ± 4.0[$]	19.5 ± 3.8[$]	−4 (−15%)	−4 (−15%)	0 (−1%)	5 (23%)	3 (15%)	6 (27%)
Path length M-L (mm)	842 ± 263[†]	405 ± 136[†]	209 ± 65[†]	−645 (−75%)	−445 (−52%)	−200 (−48%)	425 (79%)	273 (43%)	198 (63%)
Path length A-P (mm)	1177 ± 233[†]	864 ± 175[†]	721 ± 138[†]	−495 (−39%)	−322 (−27%)	−137 (−17%)	305 (32%)	203 (20%)	284 (36%)

F_{mean}, mean force during balance test; F_{max}, maximal force during the balance test, F_{min}, minimal force during the balance test; SD, standard deviation of the force over time; COP, center of pressure; M-L, medio-lateral; A-P, anterio-posterior; [†]significantly different to the other two methods; [$]different to AMTI force plate; [‡]different to PedarX.

Walking and running (Table 1)

Force–time graphs for slow walking, fast walking and running are illustrated in Figure 3(A)–(C).

The ground contact time with OpenGo was in high accordance with the reference systems, particularly, when compared to AMTI: $d = −2\%$ to $−1\%$, $r = 0.86–0.94$, LoA = 3–12% (AMTI), $d = −12\%$ to $−4\%$, $r = 0.65–0.94$, LoA = 4–12% (PedarX). Larger discrepancies were observed when comparing running data of OpenGo and PedarX.

The force impulse with OpenGo was generally lower. The difference increased with the increasing speed, and the correlation was particularly low for running: $d = −32\%$ to $−24\%$, $r = 0.52–0.88$, LoA = 20–29% (AMTI), $d = −35\%$ to $−30\%$, $r = 0.66–0.94$, LoA = 12–21% (PedarX).

The first force peak with OpenGo was significantly lower: $d = −35\%$ to $−44\%$, $r = 0.35–0.73$, LoA = 34–41% (AMTI), $d = −35\%$ to $−38\%$, $r = 0.42–0.75$, LoA = 27–31% (PedarX). For the second force peak, higher agreement was observed: $d = −19\%$ to $−21\%$, $r = 0.80–0.91$, LoA = 16–19% (AMTI), $d = −26\%$ to $−29\%$, $r = 0.82–0.90$, LoA = 16–17% (PedarX). For the local force minima, large differences in magnitude were found while correlations were high: $d = −38\%$ to $−35\%$, $r = 0.94$, LoA = 19–26% (AMTI), $d = −43\%$, $r = 0.92–0.91$, LoA = 15–28% (PedarX).

The time to the first force peak with OpenGo was significantly longer, in particular, for running: $d = 22–38\%$, $r = 0.43–0.72$, LoA = 21–41% (AMTI), $d = 12–33\%$, $r = 0.48–0.77$, LoA = 20–37% (PedarX). In contrast, the time to the second force peak was in much better accordance: $d = 8$ and 10%,

Table 4. Comparison of kinetic and kinematic variables during different specific imitation motions between the AMTI force plate, PedarX and OpenGo.

	mean ± SD			Bias (%)			95% limits of agreement (% grouped mean)		
	AMTI	PedarX	OpenGo	OpenGo vs. AMTI	PedarX vs. AMTI	OpenGo vs. PedarX	OpenGo vs. AMTI	PedarX vs. AMTI	OpenGo vs. PedarX
Back–Forth Jump									
GCT (s)	$0.66 \pm 0.16^{\dagger}$	$0.78 \pm 0.15^{\dagger}$	$0.81 \pm 0.17^{\dagger}$	0.15 (22%)	0.11 (17%)	0.03 (5%)	0.05 (7%)	0.07 (10%)	0.09 (12%)
Impulse (Ns)	726 ± 180	727 ± 158	$480 \pm 111^{\dagger}$	−242 (−34%)	7 (0%)	−250 (−34%)	167 (28%)	141 (20%)	153 (26%)
F_{peak1} (N)	$1540 \pm 297^{\dagger}$	$1352 \pm 145^{\dagger}$	$855 \pm 143^{\dagger}$	−725 (−45%)	−188 (−12%)	−537 (−37%)	545 (46%)	445 (30%)	396 (36%)
F_{min} (N)	1009 ± 144	1029 ± 117	$700 \pm 155^{\dagger}$	−337 (−31%)	28 (2%)	−365 (−32%)	344 (41%)	186 (18%)	367 (43%)
F_{peak2} (N)	1352 ± 160	1276 ± 119	$910 \pm 173^{\dagger}$	−467 (−33%)	−70 (−6%)	−397 (−29%)	272 (24%)	259 (24%)	316 (29%)
tF_{peak1} (s)	$0.08 \pm 0.03^{\dagger}$	$0.104 \pm 0.03^{\dagger}$	$0.195 \pm 0.03^{\dagger}$	0.12 (160%)	0.03 (39%)	0.09 (88%)	0.06 (46%)	0.03 (32%)	0.06 (40%)
tF_{min} (s)	0.31 ± 0.10	$0.34 \pm 0.10^{\$}$	$0.36 \pm 0.06^{\$}$	0.06 (15%)	0.02 (8%)	0.04 (6%)	0.12 (36%)	0.06 (19%)	0.15 (44%)
tF_{peak2} (s)	0.53 ± 0.16	0.53 ± 0.16	$0.59 \pm 0.16^{\dagger}$	0.07 (12%)	0.00 (1%)	0.06 (12%)	0.09 (16%)	0.05 (9%)	0.10 (18%)
Sideward Skating Jump									
GCT (s)	$0.80 \pm 0.35^{\dagger}$	$0.90 \pm 0.35^{\dagger}$	$0.94 \pm 0.36^{\dagger}$	0.14 (18%)	0.11 (13%)	0.04 (4%)	0.06 (8%)	0.05 (7%)	0.09 (11%)
Impulse (Ns)	811 ± 269	832 ± 213	$566 \pm 181^{\dagger}$	−228 (−30%)	33 (3%)	−262 (−32%)	217 (34%)	161 (21%)	143 (22%)
F_{peak1} (N)	$1843 \pm 519^{\dagger}$	$1505 \pm 330^{\dagger}$	$911 \pm 146^{\dagger}$	−1001 (−51%)	−357 (−18%)	−643 (−39%)	886 (62%)	691 (40%)	508 (41%)
F_{min} (N)	986 ± 296	1040 ± 309	$673 \pm 194^{\dagger}$	−332 (−32%)	66 (6%)	−399 (−35%)	320 (38%)	186 (18%)	364 (41%)
F_{peak2} (N)	1384 ± 247	1392 ± 212	$1004 \pm 195^{\dagger}$	−405 (−27%)	13 (1%)	−419 (−28%)	406 (35%)	233 (17%)	408 (35%)
tF_{peak1} (s)	$0.09 \pm 0.06^{\dagger}$	$0.11 \pm 0.06^{\dagger}$	$0.21 \pm 0.04^{\dagger}$	0.12 (128%)	0.02 (24%)	0.10 (84%)	0.07 (49%)	0.02 (25%)	0.07 (44%)
tF_{min} (s)	$0.36 \pm 0.26^{\dagger}$	$0.40 \pm 0.26^{\dagger}$	$0.44 \pm 0.25^{\dagger}$	0.08 (23%)	0.04 (10%)	0.04 (11%)	0.12 (35%)	0.08 (25%)	0.11 (32%)
tF_{peak2} (s)	$0.65 \pm 0.38^{\dagger}$	$0.66 \pm 0.38^{\dagger}$	$0.70 \pm 0.36^{\dagger}$	0.06 (9%)	0.02 (2%)	0.04 (6%)	0.06 (10%)	0.03 (5%)	0.06 (10%)
Single-Leg Diagonal Jump									
GCT (s)	0.28 ± 0.04	$0.38 \pm 0.06^{\$}$	$0.39 \pm 0.05^{\$}$	0.10 (36%)	0.10 (33%)	0.00 (2%)	0.04 (12%)	0.07 (20%)	0.09 (23%)
Impulse (Ns)	402 ± 71	403 ± 56	$2157 \pm 34^{\dagger}$	−141 (−36%)	5 (0%)	−146 (−36%)	116 (36%)	77 (19%)	93 (28%)
F_{max} (N)	2297 ± 360	2089 ± 169	$1307 \pm 170^{\dagger}$	−1002 (−43%)	−201 (−9%)	−792 (−37%)	693 (38%)	694 (29%)	430 (25%)
tF_{max} (s)	0.11 ± 0.06	$0.15 \pm 0.03^{\dagger}$	$0.17 \pm 0.05^{\dagger}$	0.06 (52%)	0.04 (31%)	0.02 (15%)	0.12 (94%)	0.09 (73%)	0.08 (52%)

GCT, ground contact time; F_{peak1}, first force peak during ground contact; F_{min}, local force minima at approximately 50% of ground contact; F_{peak2}, second force peak during ground contact; t_{Fpeak1}, time to first force peak; †significantly different to the other two methods; $^{\$}$different to AMTI force plate; ‡different to PedarX.

$r = 0.92$ and 0.91, LoA = 6 and 11% (AMTI), $d = 6\%$, $r = 0.87$ and 0.92, LoA = 7 and 10% (PedarX). The time to the local force minima was longer: $d = 8\%$ and 10%, $r = 0.52$ and 0.77, LoA = 23% and 16% (AMTI), $d = 9\%$ and 6%, $r = 0.52$ and 0.69, LoA = 26% and 18% (PedarX). Heteroscedasticity was found for all force impulses and peak forces between OpenGo versus AMTI and OpenGo versus PedarX.

Jumping (*Table 2 and Figure 4(A) & 4(B)*)

For the counter movement jump, the measured weight, force impulse and peak force were relatively low with OpenGo: $d = −13\%$ to $−20\%$, $r = 0.77–0.83$, LoA = 20–25% (AMTI), $d = −19\%$ to $−25\%$, $r = 0.56–0.79$, LoA = 20–33% (PedarX). The time to peak force and flight time were almost equal among all systems, and were highly correlated: $d = 1–3\%$, $r = 0.92–0.98$, LoA = 23% and 6% (AMTI), $d = 4–8\%$, $r = 0.90–0.94$, LoA = 19% and 17% (PedarX). The peak force during landing was clearly lower, but highly correlated: $d = −69\%$, $r = 0.91$, LoA = 72% (AMTI), $d = −55\%$, $r = 0.93$, LoA = 37% (PedarX).

For the drop jump, the force impulse and peak force with OpenGo were considerably lower: $d = −25\%$ and $−59\%$, $r = 0.74$ and 0.35, LoA = 32% and 57% (AMTI), $d = −29\%$ and $−52\%$, $r = 0.78$ and 0.35, LoA = 26 and 44% (PedarX). The time to peak force was clearly prolonged: $d = 176\%$, $r = 0.67$, LoA = 36% (AMTI), $d = 100\%$, $r = 0.61$, LoA = 36% (PedarX). Strong agreement was found for the ground contact time and the flight time, in particular with AMTI: $d = −2\%$ and 1%, $r = 0.99$, LoA = 7% and 4% (AMTI), $d = −11\%$ and 7%, $r = 0.96$, LoA = 13% and 9% (PedarX). Heteroscedasticity was determined for the force peak during landing in the counter movement jump and drop jump between all three systems.

Balance (*Table 3 and Figure 5(A) & 5(B) and 6(A) & 6(B)*)

During the single leg balance test, the mean and maximal force with OpenGo were similar to the other two systems: $d = 5\%$ and 17%, $r = 0.59$ and 0.51, LoA = 30% and 48% (AMTI), $d = −6\%$ and 4%, $r = 0.60$ and 0.54, LoA = 27% and 36% (PedarX). In contrast, the minimal force with OpenGo was clearly lower: $d = −27\%$, $r = 0.70$, LoA = 30% (AMTI), $d = −32\%$, $r = 0.67$, LoA = 28% (PedarX). The variation of the force values, represented by the standard deviation, was considerably high with OpenGo, not correlated and with a high LoA: $d = 708\%$, $r = 0.11$, LoA = 95% (AMTI), $d = 213\%$, $r = 0.22$, LoA = 78% (PedarX). The COP data (amplitude, standard deviation and path length) in the medio-lateral direction were generally low with OpenGo: $d = −58\%$ to $−71\%$, $r = 0.37–0.72$, LoA = 50–74% (AMTI), $d = −38\%$ to $−28\%$, $r = 0.53–0.82$, LoA = 27–46% (PedarX). In the anterio-posterior direction, OpenGo showed values in agreement with the reference systems but high LoA: $d = −16\%$ to $−3\%$, $r = 0.66–0.80$, LoA = 48–78% (AMTI), $d = −3\%$ to 19%, $r = 0.63–0.74$, LoA = 58–72% (PedarX). During the Y-Excursion Balance test, the data analysis revealed results that are essentially similar to the single leg balance test, as can be observed in Table 3. Data was heteroscedastic between all three systems as regards the path length variables.

Imitation motions (*Table 4, Figures 7(A)–(C)*)

For all three imitation drills, the ground contact time with OpenGo (determined from the pressure distribution data only) was longer compared to AMTI, and similar to PedarX: $d = 18–22\%$, $r = 0.77–1.0$, LoA = 7–12% (AMTI), $d = 4–9\%$, $r = 0.90–0.99$, LoA = 11–23% (PedarX). The force impulses, peak forces and local force minima were lower with OpenGo:

−51% to −27%, $r = 0.31$–0.95, LoA = 28–36%, 24–62% and 38–41% (AMTI), $d = -39\%$ to −28%, $r = 0.01$–0.95, LoA = 22–28%, 25–41% and 41–43% (PedarX). For the force impulse, the correlation coefficients were high for the back–forth jump and the sideward skating jump, while it was low during the single-leg diagonal jump. For the first force peak and the local minima, only low non-significant correlations were noted during the back–forth jump, while higher correlation was found for the sideward skating jump and the single-leg diagonal jump. The time to the first force peak was longer for OpenGo compared with the other systems and demonstrated high LoA: $d = 38$–160%, $r = 0.43$–0.86, LoA = 46–94% (AMTI), $d = 33$–88%, $r = 0.48$–0.84, LoA = 40–52% (PedarX). The time to the local force minima and the time to the second force peak, both of which apply to the back–forth jump and the sideward skating jump only, showed good accordance with the reference systems, a high degree of correlation and especially for the second force peak acceptable LoA: $d = 9$–23%, $r = 0.81$–1.0, LoA = 10–36% (AMTI), $d = 6$–12%, $r = 0.69$–1.0, LoA = 10–44% (PedarX). Heteroscedasticity was found for all force impulses and peak forces between all three systems.

Discussion and implications

The current study focused on the validation of the OpenGo sensor insole system compared to the AMTI force plate system and the PedarX system (gold standard for sensor insoles)

during walking, running, jumping, body balance and special imitation motions specific to the cross-country skiing.

Due to that OpenGo provides both plantar pressure and acceleration data, which is of great value for the temporal analysis. By combining pressure and acceleration, the OpenGo ground contact times and flight times during walking, running and jumping are similar to those of AMTI with no or minimal bias (−2 to 1%) and LoAs of 3–12%. Consequently, with the OpenGo sensor insoles, accurate detection of cycle characteristics during gait and temporal parameters for jump diagnostics can be provided, demonstrating equal to even higher performance than the PedarX system. The algorithm was not yet adapted to the specific imitation drills. Therefore, based on the plantar pressure distribution data, ground contact times were slightly longer when compared to AMTI (18–36%) and PedarX (4–5%), especially during the single-leg diagonal jump.

Globally, the force–time curves revealed comparable shapes between the three systems across all measurement situations (see Figures 3–7). The force impulses were 13–36% lower with the OpenGo system with LoAs of 20–36% when compared to the AMTI force plate system across all walking, running, jumping and imitation trials. The greatest differences were found during the imitation drills and running, while the highest agreement was found during the counter movement jump (−13%, LoA = 22%). The PedarX system demonstrated higher agreement to AMTI, with 0–10% higher force impulses and LoAs of 16–23% across all situations. Despite the
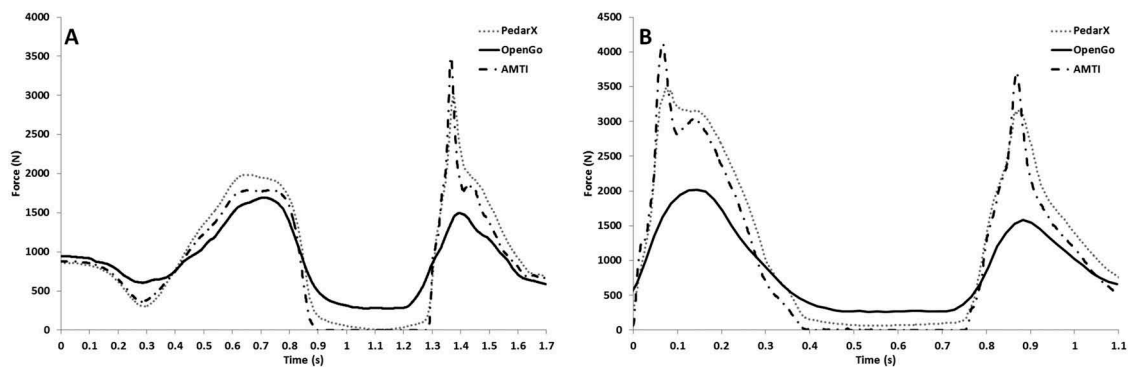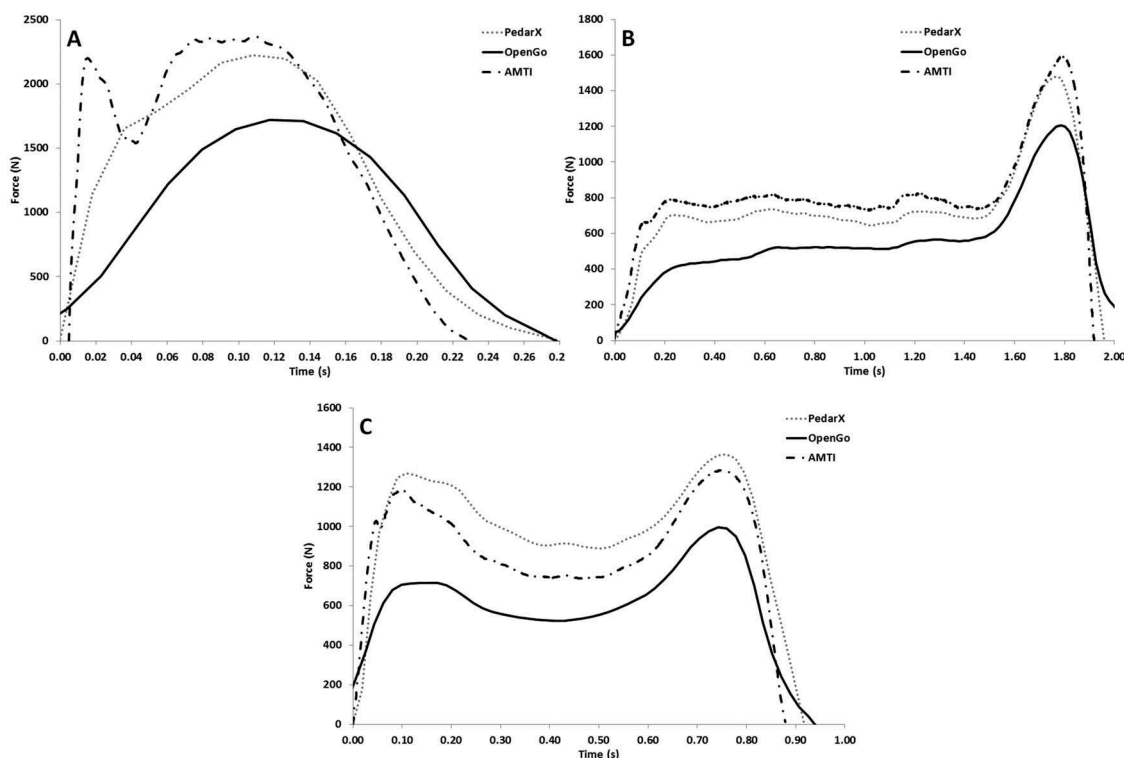

Figure 4. Time course of the total forces recorded by the AMTI force plate, the PedarX and OpenGo sensor insole systems during the counter movement jump (A) and drop jump (B) of one representative participant. The data represents the mean of four time-normalised cycles.
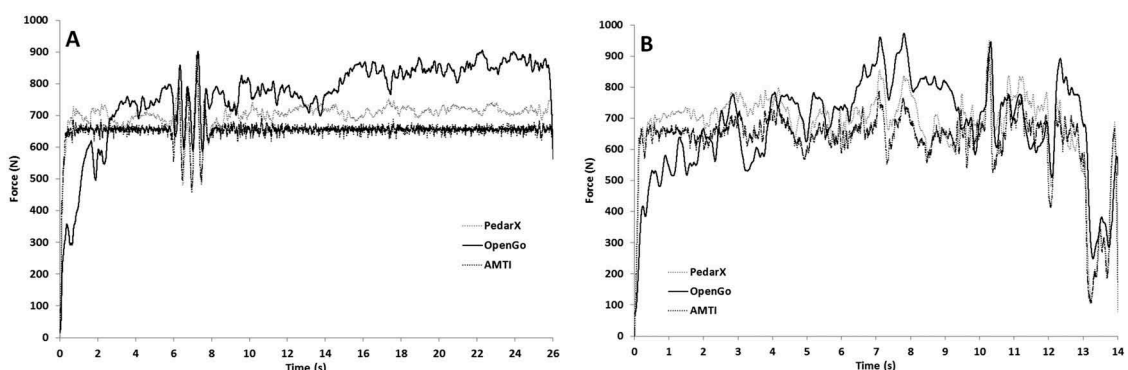
Figure 5. Time course of the total forces recorded by the AMTI force plate, the PedarX and OpenGo sensor insole systems during one single-legged balancing (A) and the Y-Excursion Balance Test (B) of one representative participant.
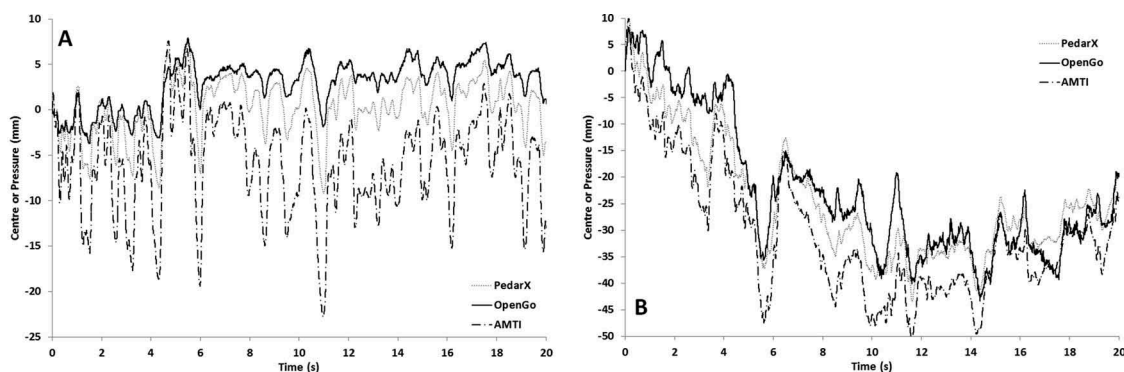
Figure 6. Time course of the centre of pressure recorded by the AMTI force plate, the PedarX and OpenGo sensor insole systems during single-legged balancing in (A) medio-lateral and (B) anterio-posterior direction.

Figure 7. Time course of the total forces recorded by the AMTI force plate, the PedarX and OpenGo sensor insole systems during the ground contact phase of one representative participant during forward-back jumps (A), sideward skating jumps (B) and single-leg diagonal jumps (C). The data represents the mean of four time-normalised cycles.

differences in some of the exercise modes, the correlations towards the AMTI for both sensor insole systems were between $r = 0.8$ and $r = 1.0$ in the majority of the test situations with slightly higher correlations for PedarX compared with OpenGo. The lowest correlation for both OpenGo and PedarX compared to AMTI were found for the force impulses during the single-leg diagonal jump and running (OpenGo: $r = 0.60$; PedarX: $r = 0.82$). Therefore, even though there were slight differences in the magnitude of the force impulses (lower for OpenGo and for the most part slightly higher for PedarX), the differences might be regarded as systematic based on the moderate to high correlations between the systems. Therefore, OpenGo yields reproducible results as regards to the force impulse that allow for relative comparison

within one subject and across multiple subjects, even if absolute values differ from the gold standard. Exceptions to this general observation are with respect to first force peak as will be discussed later and impulse values in some exercise modes.

The shorter the ground contact times, the steeper the rise in the force curve, the higher the ground reaction forces (i.e., running, drop jump, single-leg diagonal jump) and the higher the impact forces (e.g., force impact during landing after jumps, fast running), the less the agreement and the higher the LoAs are observed between the OpenGo and the AMTI force plate, while the PedarX system demonstrated greater robustness here. In addition, the data was found to be heteroscedastic with regards to these variables. Therefore, the higher the measured forces, the greater the discrepancy between the

three systems. This might be attributed to differences in the response of the capacitive sensors between the OpenGo and PedarX. With OpenGo, a distinct latency in the rise and fall of the measured forces at the start and end of the ground contact was detected. In the case of longer ground contact times, the OpenGo force signal became closer to the true forces (as detected by AMTI), while during very short ground contact times, the rise in the force curve was too slow and delayed to reveal sufficient agreement. Note that the later the analysed event within the ground contact phase (e.g., first force peak vs. second force peak), the greater agreement (−35 to −51% vs.-19 to −33%) and more narrow LoAs (34–62% vs. 16–35%) were found with OpenGo. This finding is in line with the studies of Hurkmans et al. (2006), Barnett, Cunningham, and West (2000) and Kalpen and Seitz (1994), where the agreement between the Pedar system and a Kistler force plate was greater for the second force peak compared with the first force peak during walking. The underestimation of the first force peak was attributed to the differences in the way matrix sensors (i.e., PedarX) measure forces compared to force plates. The matrix sensors measure forces perpendicular to each sensor, especially during heel strike and toe-off; hence, the force vector of each sensor is different from the vertical force vector of the force plate (Hurkmans et al., 2006).

Regarding the temporal parameters time to first peak, time to local force minima and time to second force peak, an equal pattern for the force data presented earlier was observed. The greatest deviation and LoAs of OpenGo when compared to AMTI and PedarX was found for the first peak during the back–forth imitation jump (160%, respectively 88% longer) and the peak force during the drop jump (176%, respectively 100% longer), while the difference was only 8–12%, respectively 6–12%, for the second force peak. Therefore, for measuring the instant and magnitude of force peaks during fast motions with a steep rise in the force curve (e.g., running, jumping, and landing), the PedarX system is better applicable than OpenGo. For motions with longer ground contact times, and for detection of force peaks later during the cycle, both sensor insole systems reveal higher agreement in magnitude, are well correlated and with more narrow LoAs.

The fact that sensor insoles measure the "normal" force, which is not necessarily similar to the vertical ground reaction force, was suggested as a limitation of these systems (Kalpen & Seitz, 1994; Kernozek et al., 1996; McPoil et al., 1995). However, the imitation drills that were selected to produce distinct shear forces on the insole were not associated with lower agreement of the measured values between the systems when compared with standard gait and jump exercises. In any case, the differences towards the force plate were not more pronounced as in the other types of motions. For the PedarX system, the force impulse was only 0–3% greater (LoA: 19–21%) when compared with the AMTI data. Therefore, sensor insoles might well be applied in types of motion where shear forces act on the insoles (e.g., skating push-off).

To the best of our knowledge, this is the first analysis of the validity of sensor insoles for balance tasks. During quiet bipedal standing, the measured forces were equal between PedarX and AMTI, while for the OpenGo system they were 20% lower

(Table 2). However, the correlation was only $r = 0.62$ between PedarX and AMTI and slightly higher ($r = 0.77$) for OpenGo with similar LoAs of 20%. In contrast, during the single-leg balance tests the mean forces with OpenGo were 2–5% higher when compared with AMTI and 6–10% lower when compared with PedarX with moderate correlation coefficients of $r = 0.55$–0.69 and identical LoAs of approximately 30%. In addition, while during the single-leg stance, almost stable force values were detected with AMTI, clear alterations in forces across the time were visible with the sensor insoles (especially OpenGo) as seen in the wider range in minimum and maximum forces. Interestingly, the balance test with greater dynamics (Y-Excursion Balance test) revealed greater agreement between the systems compared with the more static single-leg balance test. In particular, the variability (SD) in force values across the balance tests were more pronounced with the two sensor insole systems when compared with the force plate data (OpenGo 190% and 708% higher, PedarX, 45% and 158% higher). This might be based on the over/underestimation of measured ground reaction forces when the pressure area on the insole is altered by changes in the foot position, foot loading and so on. The LoAs regarding the force variability were among the worst in all measured parameters with values between 86% and 95% for OpenGo and between 57% and 71% for PedarX.

The COP time courses during the two balance tasks revealed comparable shapes between the three systems (Figure 6). However, compared to force plate data, greatly underrepresented deviations in the medio-lateral direction were found for both sensor insole systems. For OpenGo, the medio-lateral deviations were 58–75% lower compared with AMTI, and 28–48% lower when compared with PedarX. The correlations to AMTI were low to moderate for OpenGo ($r = 0.37$–0.78) and moderate to high to PedarX ($r = 0.53$–0.82). For the anterio-posterior direction, higher agreement was found between the sensor insoles and force plate data with OpenGo, revealing approximately 39% lower values compared with AMTI ($r = 0.66$–0.86) and 17% lower values compared with PedarX ($r = 0.91$–0.96). Consequently, when using sensor insole systems, the analysis of COP data in the medio-lateral direction, in particular, should be considered with care, while anterio-posterior direction reveals quite high agreement. However, the wide LoAs for all measures of COP and path length data, with values between 23% and 79% for OpenGo and between 15% and 57% for PedarX and slightly better values during the Y-Excursion test should be considered. The lower magnitude in the deviation of the COP data with the sensor insoles might be in part attributed to the differences in the sampling rate between the systems (50 Hz vs. 1000 Hz).

Conclusion

The current study demonstrates that the OpenGo system reproduces ground reaction forces during walking, running, jumping and special imitation motions with lower force impulses of approximately 13–36% when compared with the AMTI force plate system, and 12–26% when compared to the PedarX system, with differences diminishing when ground contact times are longer and forces lower (e.g., walking vs. drop jump). The basic shapes of the force curves and the correlations between the three systems demonstrated high

agreement in the majority of values. Exact determination – ahead of PedarX – of cycle characteristics during gait and jumping tasks (e.g., ground contact time, swing time and flight time) can be achieved when combining the pressure distribution and internal accelerometer data of the OpenGo system. With regard to forces, very short ground contact times with force impacts cannot be determined accurately by the OpenGo system, even though the correlations of the distinctly lower values were high in the majority of analysed variables. This suggests that OpenGo may still be applicable in these cases as long as comparative conclusions are sufficient. During balance tasks, the sensor insole systems revealed greater deviation in the forces, but less deviation in the COP data when compared with force plate data. Greater discrepancy in COP deviation was found in the medio-lateral direction, while the anterio-posterior direction was closer to force plate data. However, the very high LoAs should be considered. Special imitation drills that aimed at producing high shear forces on the sensor insoles were not associated with less accurate data as compared with standard measures during gait and jumps; therefore, the application of sensor insoles during types of locomotion where shear forces might be exaggerated (i.e., skating push-off) are warranted. In conclusion, when high accuracy in the absolute values of measured plantar forces is required, the PedarX sensor insole system is preferable, while OpenGo reveals distinctly lower forces and latency in the force kinetics during loading and unloading, especially during fast motions. For detection of cycle characteristics and temporal parameters during gait and jumping tasks, the OpenGo system demonstrates almost perfect agreement with force plate data and, therefore, is recommended. With awareness of the system's limitations, the OpenGo sensor insole system can be applied to both clinical and research settings to evaluate the temporal and force parameters during the different types of gait and jumping tasks. Furthermore, the wireless system with both telemetric and internal data storage, with no extra equipment necessary for data storage and/or transmission, allows for quick analysis, as well as speedy feedback and measurement under complex field conditions such as trail running, jumping and cross-country skiing with low hindrance of the user by the measurement equipment.

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