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The Optimization of the Number and Positions of Foot Pressure Sensors to Develop Smart Shoes

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Objective: The purpose of this study was to optimize the number and positions of foot pressure sensors using the reliability analysis of the center of pressure (COP) in smart shoes.

Background: Foot pressure can be different according to foot region, and it is important which region of the foot pressure needs to be measured.

Method: Thirty adults (age: 20.5±1.8 years, body weight: 71.4±6.5kg, height: 1.76±0.04m) participated in this study. The foot pressure data were collected using the insole of Pedar-X system (Novel GmbH, USA) with a sampling frequency of 100Hz during 1.3m/s speed walking on the treadmill (Instrumented treadmill, Bertec, USA). The intraclass correlation coefficients (ICC) were calculated between the COP positions using 4, 5, 6, 7, 8, and 99 sensors, while one-way repeated measure ANOVA was performed between the standard deviation (SD) of the COP positions.

Results: The medio-lateral (M/L) COP position using 99 sensors was positively correlated with the M/L COP positions using 6, 7, and 8 sensors; however, it was not correlated with the M/L COP positions using 4 and 5 sensors during landing phase (1~4%) ($p<.05$). The antero-posterior (A/P) COP position using 99 sensors was positively correlated with the A/P COP positions using 4, 5, 6, 7, and 8 sensors ($p<.05$). The SD of the COP position using 99 sensors was smaller than the SD of the M/L COP positions using 4, 5, 6, 7, and 8 sensors ($p<.05$).

Conclusion: Based on our findings, it is desirable to arrange at least 6 sensors in smart shoes.

Application: The study of optimizing the number and positions of foot pressure sensors would contribute to developing more effective smart shoes using foot pressure technology.

Keywords: Smart shoes, Optimization, Foot pressure sensors, Center of pressure

1. Introduction

Walking is the most basic forms of mobility revealed with the complex movements of upper and lower extremities, and it shows various aspects of human locomotion according to physical characteristics, gait speed, habit, and character. Walking can cause imbalance in human structure by wrong habits or postures, and thus diseases or injuries can occur (Scott and Winter, 1990; Tirosh and Sparrow, 2005; Whittle, 1990; Yoo et al., 2016). The foot striking the ground first plays the most prominent role in preventing wounds and injuries that may be caused during the walking process and in controlling risk factors. Therefore, a variety of types of shoes have been developed to alleviate impact to human body and protect feet during walking. Shoes are used to absorb impact to human body during the walking process, mitigate foot fatigue and pain, and prevent injuries (Park et al., 2014; Stewart et al., 2009).

With the development of shoes' function and role, new types of smart shoes using various information technology (IT) to provide health information and exercise prescription, as well as to prevent injuries, are being developed. Such smart shoes measure and provide the levels of exercise and energy consumption quantitatively, in addition to basic information of gait (Seo and Jang, 2015; Shim et al., 2015). Nike developed a monitoring system linked with the iPod and iPhone, being embedded with a single acceleration sensor module at the center of a shoe and releasing the shoes in 2009 for the first time. In 2014, Adidas launched a system embedded with a sensor at the shoe heel, with a heart rate measuring band on the chest additionally. Recently, Xiaomi and Li-Ning collaborated and launched Li-Ning Smart. As such, smart shoes are continuously developed (Shu et al., 2010).

However, most smart shoes using IT are utilized to offer basic gait parameters, simple index for exercise level, and energy consumption through gait count analysis (Park et al., 2014; Seo and Jang, 2015). Because it is difficult to determine walking characteristics with just simple gait parameters, there is limitation in mitigating foot pain or improving body imbalance due to wrong walking habits (Shim et al., 2015). For this reason, the development of smart shoes, through which walking characteristics can be utilized and stability and balance can be measured, is required.

To solve the downfalls of current smart shoes and to precisely monitor walking, foot pressure sensors are used, with the gait factors estimated through pressure measures on the ground. In the kinematical factors, the force or pressure on the ground was analyzed using a force plate or a foot pressure system, major walking factors were identified, and stability and balance, as well as joint force and muscle moment to lower extremities, were calculated. Various types of gait were analyzed by installing pressure-measurable sensors to the insole of shoes (Razak et al., 2012). A foot always contacting the ground puts pressure on the ground naturally, and the pressure distribution to the ground varies according to human body movement. Therefore, the type, characteristics, stability, and balance of walking can be evaluated through foot pressure distribution. Foot pressure can be different according to foot region, and it is important which region of the foot pressure needs to be measured (Razak et al., 2012).

The foot regions playing an important role in supporting body weight and controlling body balance can be divided into fifteen areas (3 regions at the heel, 2 at the midfoot, 5 at the metatarsal, and 5 at the toe). The force to each region is used to examine physical functions, structure, and functional information of the whole body or lower extremities (Shu et al., 2010).

Pappas et al. (2004) attached 3 pressure sensors to the heel and both metatarsals, and Bamberg et al. (2008) attached 5 pressure sensors to both heels, both metatarsals, and hallux in order to analyze walking. Hessert et al. (2005) divided foot regions into 9 areas (medial calcaneus, lateral calcaneus, medial arch, lateral arch, first metatarsal, two-three metatarsals, four-five metatarsals, hallux, and toes) on the basis of anatomical foot structure. They comparatively analyzed foot pressure distribution revealed in the walking process of adults and elderly people. Shu et al. (2010) attached 6 pressure sensors including the insole heel and metatarsal in order to reduce foot pressure sensors' complexity, and estimated the COP according to static posture. As a result of comparing with a force plate, they reported that 5% error occurred on average. Park et al. (2014) compared a new prototype of smart shoes embedded with 5-foot pressure sensor modules according to the COP trajectory revealed in walking with the Pedar-X mobile system of Novel GmbH. Shim et al. (2015) classified the types of walking by attaching 6 foot pressure sensors based on medical sole. Lee et al. (2016) analyzed walking by attaching 5 foot pressure sensors.

Although the previous studies have investigated the reliability of the foot pressure sensor positions compared with the force plate or foot pressure system, the sensor positions on the foot were set without any anatomical references in most studies. In addition, limitations were revealed in precisely evaluating a human body's dynamic movements including walking, as comparisons were made through scoring the ordinal scale of positions' pressure values. In this regard, studies to optimize the number and positions of foot pressure sensors are essentially needed to provide gait information by inserting a limited number of pressure sensors into shoes.

This study aimed to present optimal pressure sensor positions to develop smart shoes embedded with precise walking analysis function through a COP position's reliability analysis according to foot pressure sensor position during walking.

2. Method

2.1 Subjects

30 male adults in their 20s (age: 20.5±1.8 years; height: 176.2±4.2cm; weight: 71.4±6.5kg) without orthopedic disease history, participated in this study.

2.2 Experiment procedures

The Pedar X system (Novel GmbH, USA) insoles embedded with 99 sensors to measure foot pressure distribution was inserted into shoes as shown in Figure 1. After wearing the shoes, the participants in this study conducted warm-up trials for 5 minutes in order to walk naturally on the treadmill. The experiment was carried out with a walking speed of 1.3m/s on the treadmill (Instrumented treadmill, Bertec, USA) used in the general gait analysis (Doke et al., 2004) (Figure 2). The 10 strides were selected for each walking condition, and the data collection was set to a sampling frequency 100Hz.

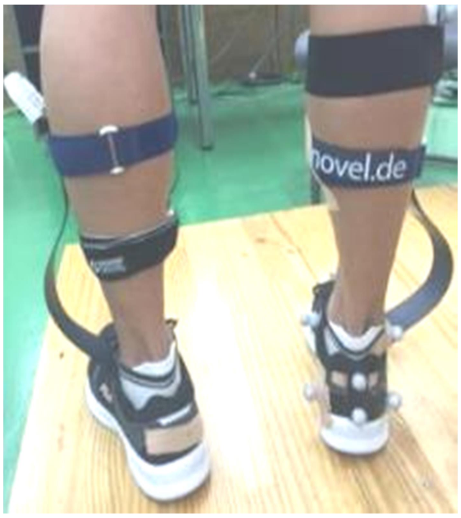

Figure 1. Wearing insole

Figure 2. Gait experiment

2.3 Data processing

Based on 425 matrix (17×52), this study measured pressure by foot position using the Pedar-X system insole where 99 sensors place (Figure 3). The A/P and M/L COP positions of supporting right foot during walking were estimated, and normalization to stance phase was carried out for the comparison between the conditions. In doing so, the estimation equation for COP positions is as follows, and Figure 3 shows a reference coordination system.

$$COP_X = \frac{\sum_{i=1}^{n} x_i p_i}{\sum_{i=1}^{n} p_i} \quad COP_Y = \frac{\sum_{i=1}^{n} y_i p_i}{\sum_{i=1}^{n} p_i}$$

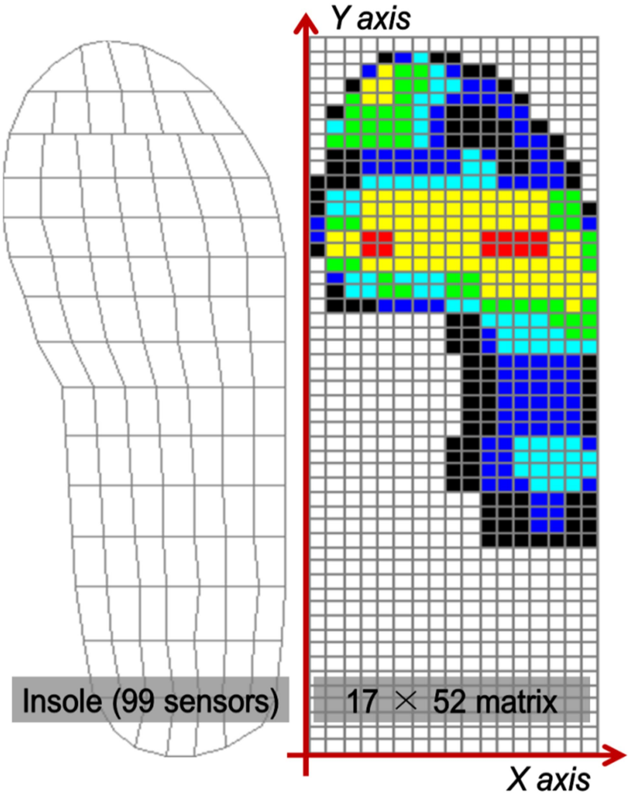

Figure 3. 17×52 matrix and reference coordination system

Here, X indicates M/L direction, and Y indicates A/P direction respectively, while p sensor's pressure value.

The sensor positions to compare with the positions of 99 sensors were set to 8 regions of the foot (interphalangeal joint [IP], metatarsophalangeal joint [MP], distal metatarsophalangeal joint [DMP], heel [H], lateral calcaneus [LC], medial talus [MT], styloid process [SP], & Tarsometatarsal joint [TM]) as shown in Figure 4 in consideration of foot's anthropometric structure and ratio (Davis, 1990; Isman and Isman, 1969; Dogan et al., 2007; Pietak et al., 2013) and based on functional anatomical positions. As for the 8 selected foot regions, the positions with bigger pressure were preferentially arranged among 15 major foot regions for weight support and balance control. Gait is carried out by contact with the ground and load; the sole regions, where high pressure exists from the aspect that close causal relationship between pressure (force) and movement exists, were selected. The sensor pressure values in Figure 3 were used as estimating each COP position.

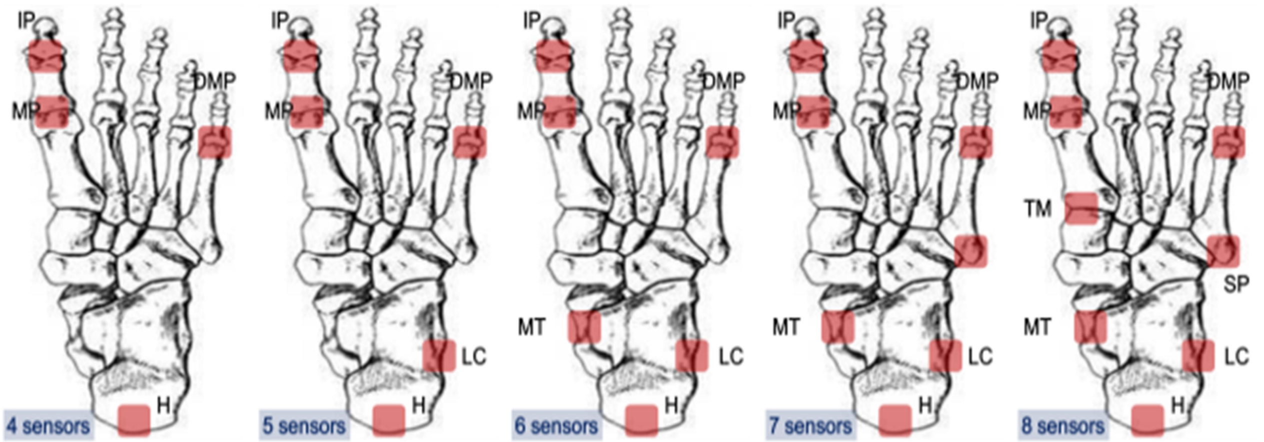

Figure 4. Sensor positions

2.4 Statistical processing

To examine the COP position closest to the COP position estimated with 99 sensors' pressure values, a reliability analysis was conducted using the intraclass correlation coefficients (ICC). ICC were calculated between the COP position using 99 sensors and the COP positions using 4, 5, 6, 7, and 8 sensors. Consistency was analyzed through repeated measure one-way ANOVA on the standard deviation of COP position from each sensor placements. In doing so, SPSS Ver. 18.0 software (IBM, USA) was used, and significance level α was .05.

3. Results

This study was undertaken to present optimal pressure sensor positions to develop smart shoes using precise walking analysis function through a COP position's reliability analysis according to foot pressure sensor position in walking. To achieve the goal, the ICC between the COP position estimated with 99 sensors' pressure values and the COP positions using 4, 5, 6, 7, and 8 sensors were calculated. Also, a repeated measure one-way ANOVA on standard deviation of COP position by each sensor placement was conducted.

Tables 1 and 2 show the mean and SD on COP positions in the right foot stance phase. Upon the observation of the M/L movement of the COP position estimated with 99 sensors, it moved inside of the foot from 54.06±2.40mm upon right heel striking the ground (1%) to 31.66±4.50mm upon the end of the right foot taking off the ground (30%). Upon looking at the A/P movement of COP, movement was made from the back to the front from 31.66±4.50mm upon the right heel striking the ground (1%) to 191.86±11.36mm upon the end of the right foot taking off the ground (30%). As shown in Figure 5, the movements of COP estimated with 4, 5, 6, 7, and 8 sensors were similar to the movement of COP estimated with 99 sensors. Tables 3 and 4 show the ICC results between the COP position estimated with 99 sensors and those estimated with 4, 5, 6, 7, and 8 sensors. The correlations between A/P COP position estimated with 99 sensors and the M/L COP positions estimated with 6, 7, and 8 sensors showed a statistically high positive correlation from the moment the right heel strikes to the moment the end of the foot takes off the ground (1~30%). The correlation coefficients with M/L COP positions estimated with 4 and 5 sensors showed a low correlation at the section where right heel strikes (1~4%), and did not show a statistically significant result. Meanwhile, in the A/P COP position, a high positive correlation was shown between the COP position estimated with 99 sensors and COP positions estimated with all other sensors, also showing a statistically significant result.

Table 5 shows the results of repeated measure one-way ANOVA by calculating the SD of COP position by sensor. The SD of M/L COP positions in the right foot stance phase showed a statistically significant result at F=49.428 level (p=.000). The effect size (partial eta square) was .630, and the statistical power was 1.000. According to the post hoc test result, the SD of M/L COP position calculated with 99 sensors was smaller than the SD of those calculated with 4, 5, 6, 7, and 8 sensors, and a statistically significant difference was shown. The SD of M/L COP position calculated with 4 sensors was smaller than that of those calculated with 5, 6, and 8 sensors, and a statistically significant result was found. The SD of A/P COP positions in the right foot stance phase, a statistically significant result was shown at F=13.505 level (p=.000) level. The effect size (partial eta square) was .318, and the statistical power was 1.000. According to the post hoc test result, the SD of A/P COP position calculated with 99 sensors was smaller than the SD of those calculated with 4, 5, 6, 7, and 8 sensors, and a statistically significant difference was shown. The SD of A/P COP position calculated with 4 sensors was larger than the SD of those calculated with 6, 7, and 8 sensors, and a statistically significant result was found.

Table 1. Descriptive information for M/L COP positions of right foot during stance phase (Unit: mm)

M/L COP position	99 sensors	4 sensors	5 sensors	6 sensors	7 sensors	8 sensors
1%	54.06±2.40	52.64±1.05	57.11±3.20	56.61±3.33	56.83±3.41	56.82±3.41
2%	54.16±2.18	52.51±1.27	57.58±2.71	56.55±2.80	57.29±3.03	57.28±3.03
3%	54.21±1.78	52.09±1.84	58.05±2.78	56.23±2.70	58.03±2.70	57.99±2.70
4%	54.08±1.82	51.67±2.55	58.07±3.05	55.69±3.00	58.58±2.51	58.31±2.54
5%	53.60±2.08	50.75±2.18	57.52±2.97	54.95±3.19	58.50±2.55	57.91±2.74
6%	52.97±2.35	49.76±2.37	56.75±2.97	54.05±3.47	58.05±2.71	57.15±3.12
7%	52.32±2.51	48.84±2.90	55.86±3.27	53.15±3.76	57.53±2.89	56.35±3.46
8%	51.72±2.66	47.94±3.41	54.85±3.68	52.22±4.09	57.03±3.08	55.67±3.76
9%	51.13±2.80	47.05±3.96	53.72±4.26	51.29±4.55	56.53±3.39	55.04±4.12
10%	50.47±2.96	46.14±4.58	52.42±4.97	50.31±5.12	55.98±3.85	54.40±4.56
11%	49.72±3.10	45.07±5.11	50.83±5.59	49.05±5.60	55.16±4.29	53.54±4.93
12%	48.95±3.17	44.20±5.41	49.33±6.04	47.86±5.94	54.33±4.73	52.66±5.24
13%	48.17±3.21	43.32±5.54	47.86±6.26	46.60±6.05	53.42±5.12	51.69±5.48
14%	47.34±3.21	42.41±5.61	46.29±6.43	45.22±6.12	52.36±5.41	50.57±5.60
15%	46.47±3.21	41.50±5.46	44.73±6.40	43.83±6.03	51.24±5.50	49.44±5.55
16%	45.58±3.23	40.54±5.32	43.22±6.26	42.48±5.87	50.05±5.60	48.25±5.52
17%	44.62±3.22	39.64±5.25	41.75±6.11	41.16±5.74	48.73±5.74	46.93±5.47
18%	43.61±3.23	38.58±5.04	40.14±5.81	39.70±5.47	47.16±5.84	45.45±5.45
19%	42.60±3.19	37.65±4.84	38.78±5.36	38.49±5.12	45.60±5.90	44.02±5.39
20%	41.55±3.10	36.63±4.70	37.34±4.92	37.16±4.76	43.75±5.84	42.39±5.27
21%	40.47±2.95	35.64±4.64	36.05±4.69	35.97±4.60	41.80±5.67	40.72±5.14
22%	39.30±2.76	34.61±4.54	34.80±4.53	34.78±4.50	39.63±5.31	38.86±4.94
23%	38.06±2.56	33.50±4.49	33.60±4.47	33.59±4.47	37.34±4.89	36.87±4.73
24%	36.87±2.36	32.40±4.44	32.47±4.43	32.47±4.43	35.17±4.65	34.91±4.61

Table 1. Descriptive information for M/L COP positions of right foot during stance phase (Continued) (Unit: mm)

M/L COP position	99 sensors	4 sensors	5 sensors	6 sensors	7 sensors	8 sensors
25%	35.72±2.23	31.08±4.44	31.13±4.41	31.13±4.41	33.03±4.51	32.86±4.49
26%	34.67±2.28	29.51±4.40	29.53±4.39	29.53±4.39	30.87±4.48	30.72±4.43
27%	33.84±2.53	28.02±4.26	28.02±4.26	28.02±4.26	28.92±4.37	28.77±4.28
28%	33.20±2.91	27.24±4.41	27.24±4.41	27.24±4.41	27.62±4.49	27.48±4.36
29%	32.61±3.17	26.42±5.46	26.42±5.46	26.42±5.46	26.58±5.44	26.56±5.29
30%	31.66±4.50	27.28±12.19	27.28±12.19	27.28±12.19	27.33±12.15	27.35±12.14

Table 2. Descriptive information for A/P COP positions of right foot during stance phase (Unit: mm)

A/P COP position	99 sensors	4 sensors	5 sensors	6 sensors	7 sensors	8 sensors
1%	35.52±7.64	14.60±6.79	23.08±7.76	23.92±8.22	25.59±10.74	25.60±10.73
2%	42.18±8.37	21.12±14.38	27.87±9.67	29.06±10.29	32.94±12.78	32.94±12.78
3%	50.78±9.53	28.58±21.20	33.80±11.90	35.30±12.37	43.55±14.57	43.64±14.61
4%	59.39±10.07	38.57±29.19	40.82±15.85	41.91±15.09	53.78±15.19	54.33±15.37
5%	66.80±10.47	48.45±34.60	47.99±20.14	48.36±17.54	61.31±15.76	62.41±15.99
6%	72.29±11.63	56.00±36.02	53.58±21.82	53.47±18.47	66.35±15.93	67.94±16.28
7%	77.33±13.07	64.24±37.69	59.71±23.91	59.03±20.02	71.22±16.83	73.11±17.19
8%	82.77±14.89	73.56±39.49	67.07±26.61	65.72±22.48	76.81±18.34	78.79±18.51
9%	88.86±16.85	84.21±42.18	75.93±30.64	73.82±26.41	83.25±20.61	85.13±20.38
10%	95.56±18.92	95.76±45.36	86.17±35.41	83.34±31.30	90.54±23.40	92.20±22.65
11%	102.75±20.71	108.45±47.35	98.08±39.66	94.61±35.76	98.94±25.97	100.28±24.69
12%	110.26±21.89	121.34±47.32	110.61±42.14	106.79±38.74	107.91±27.72	108.88±26.01
13%	117.80±22.32	133.61±45.79	122.82±42.57	118.77±39.77	116.92±28.58	117.48±26.45
14%	125.25±22.30	145.29±43.12	135.05±41.80	130.94±39.67	126.01±28.79	126.17±26.36
15%	132.50±21.98	156.12±39.63	146.84±39.72	142.70±38.29	134.85±28.14	134.51±25.69
16%	139.45±21.53	165.76±35.62	157.53±36.75	153.56±36.11	143.27±27.13	142.44±24.77
17%	146.24±20.74	174.31±31.70	167.48±33.51	163.91±33.66	151.55±25.85	150.23±23.60
18%	153.06±19.56	182.05±26.65	176.81±29.20	173.55±29.87	159.73±23.94	157.90±22.08
19%	159.67±17.82	188.75±20.51	184.73±23.44	182.10±24.52	167.52±21.21	165.30±19.95
20%	166.22±15.62	194.07±14.12	191.55±17.09	189.50±18.20	175.03±18.03	172.55±17.53
21%	172.29±13.13	198.05±8.07	196.52±10.45	195.24±11.23	181.70±14.12	179.12±14.50
22%	177.81±10.73	200.77±4.52	200.03±5.75	199.43±5.99	187.71±10.27	185.26±11.31
23%	182.56±9.16	202.33±3.71	201.98±4.45	201.85±4.44	192.69±7.64	190.52±8.83
24%	186.38±8.52	203.24±3.61	202.97±4.15	202.96±4.15	196.44±6.50	194.71±7.57

Table 2. Descriptive information for A/P COP positions of right foot during stance phase (Continued) (Unit: mm)

A/P COP position	99 sensors	4 sensors	5 sensors	6 sensors	7 sensors	8 sensors
25%	189.43±8.25	204.29±3.70	204.12±3.99	204.12±3.99	199.59±5.74	198.04±6.92
26%	191.84±8.14	205.80±3.89	205.73±3.97	205.73±3.97	202.62±5.44	200.94±6.90
27%	193.69±7.93	208.35±4.10	208.35±4.10	208.35±4.10	206.26±5.31	204.03±7.41
28%	195.02±7.35	212.27±4.69	212.27±4.69	212.27±4.69	211.40±5.65	208.36±8.43
29%	195.21±7.40	214.98±5.87	214.98±5.87	214.98±5.87	214.60±6.21	211.90±8.64
30%	191.86±11.36	210.91±10.81	210.91±10.81	210.91±10.81	210.79±10.83	210.65±10.80

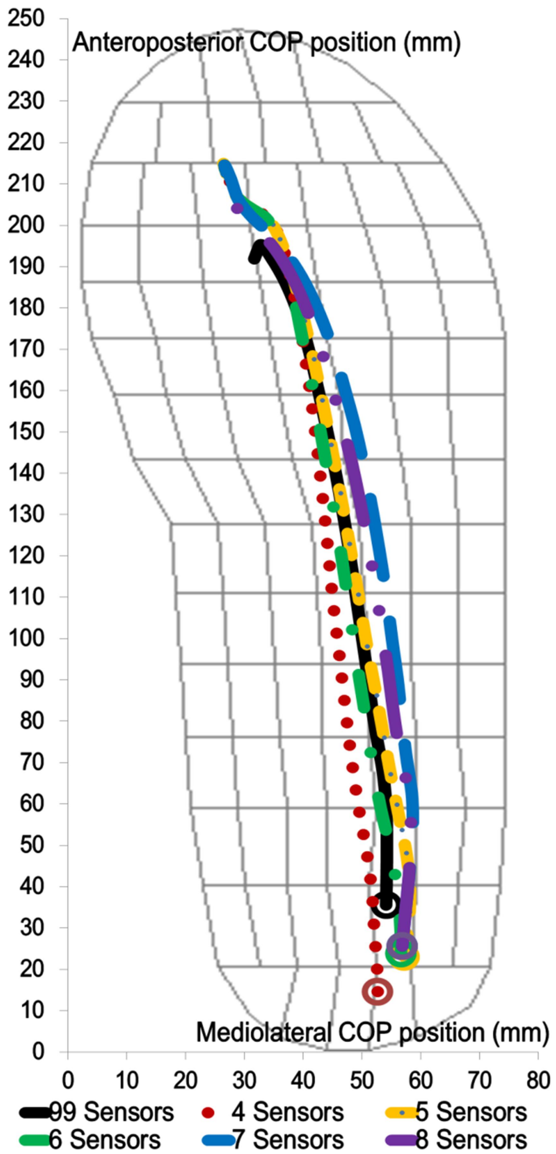

Figure 5. COP trajectory of right foot during stance phase

Table 3. Descriptive information for ICC between M/L COP position calculated using 99 sensors and other COP positions

M/L COP	4 sensors		5 sensors		6 sensors		7 sensors		8 sensors	
	r	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*
1%	.576	.012*	.333	.141	.648	.003*	.638	.004*	.638	.004*
2%	.259	.212	.241	.231	.754	.000*	.775	.000*	.775	.000*
3%	.153	.329	.104	.385	.780	.000*	.765	.000*	.766	.000*
4%	.303	.169	.259	.212	.787	.000*	.792	.000*	.828	.000*
5%	.614	.006*	.491	.037*	.816	.000*	.852	.000*	.903	.000*
6%	.782	.000*	.675	.002*	.843	.000*	.881	.000*	.923	.000*
7%	.800	.000*	.757	.000*	.844	.000*	.886	.000*	.923	.000*
8%	.811	.000*	.807	.000*	.845	.000*	.891	.000*	.919	.000*
9%	.810	.000*	.831	.000*	.840	.000*	.897	.000*	.915	.000*
10%	.801	.000*	.835	.000*	.828	.000*	.893	.000*	.902	.000*
11%	.781	.000*	.825	.000*	.816	.000*	.886	.000*	.889	.000*
12%	.770	.000*	.810	.000*	.803	.000*	.874	.000*	.872	.000*
13%	.763	.000*	.800	.000*	.793	.000*	.864	.000*	.858	.000*
14%	.743	.000*	.780	.000*	.778	.000*	.853	.000*	.846	.000*
15%	.740	.000*	.770	.000*	.771	.000*	.849	.000*	.842	.000*
16%	.737	.000*	.771	.000*	.770	.000*	.850	.000*	.841	.000*
17%	.730	.000*	.769	.000*	.768	.000*	.849	.000*	.844	.000*
18%	.732	.000*	.778	.000*	.776	.000*	.853	.000*	.851	.000*
19%	.717	.001*	.783	.000*	.776	.000*	.851	.000*	.852	.000*
20%	.686	.001*	.766	.000*	.759	.000*	.846	.000*	.852	.000*
21%	.652	.003*	.714	.001*	.710	.001	.837	.000*	.842	.000*
22%	.636	.004*	.667	.002*	.665	.002	.828	.000*	.827	.000*
23%	.632	.004*	.642	.004*	.642	.004	.815	.000*	.805	.000*
24%	.643	.004*	.650	.003*	.650	.003	.791	.000*	.778	.000*
25%	.661	.002*	.664	.002*	.664	.002	.771	.000*	.758	.000*
26%	.697	.001*	.697	.001*	.697	.001	.776	.000*	.763	.000*
27%	.727	.000*	.727	.000*	.727	.000*	.792	.000*	.779	.000*
28%	.739	.000*	.739	.000*	.739	.000*	.787	.000*	.777	.000*
29%	.736	.000*	.737	.000*	.737	.000*	.760	.000*	.764	.000*
30%	.649	.003*	.649	.003*	.649	.003*	.650	.003*	.649	.003*

*Indicates statistically significant difference $p<.05$

Table 4. Descriptive information for ICC between A/P COP position calculated using 99 sensors and other COP positions

A/P COP	4 sensors		5 sensors		6 sensors		7 sensors		8 sensors	
	r	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*
1%	.639	.004*	.837	.000*	.873	.000*	.857	.000*	.857	.000*
2%	.712	.001*	.817	.000*	.835	.000*	.847	.000*	.847	.000*
3%	.712	.001*	.883	.000*	.880	.000*	.884	.000*	.885	.000*
4%	.642	.004*	.845	.000*	.864	.000*	.875	.000*	.884	.000*
5%	.590	.010*	.772	.000*	.830	.000*	.856	.000*	.873	.000*
6%	.600	.008*	.767	.000*	.835	.000*	.868	.000*	.891	.000*
7%	.620	.006*	.776	.000*	.849	.000*	.882	.000*	.904	.000*
8%	.661	.002*	.802	.000*	.871	.000*	.902	.000*	.919	.000*
9%	.692	.001*	.814	.000*	.881	.000*	.917	.000*	.929	.000*
10%	.713	.001*	.816	.000*	.879	.000*	.927	.000*	.935	.000*
11%	.741	.000*	.818	.000*	.877	.000*	.934	.000*	.941	.000*
12%	.767	.000*	.820	.000*	.875	.000*	.938	.000*	.944	.000*
13%	.785	.000*	.824	.000*	.876	.000*	.941	.000*	.947	.000*
14%	.802	.000*	.828	.000*	.878	.000*	.942	.000*	.949	.000*
15%	.818	.000*	.835	.000*	.882	.000*	.945	.000*	.951	.000*
16%	.840	.000*	.851	.000*	.893	.000*	.950	.000*	.957	.000*
17%	.855	.000*	.864	.000*	.900	.000*	.956	.000*	.962	.000*
18%	.870	.000*	.878	.000*	.911	.000*	.961	.000*	.968	.000*
19%	.881	.000*	.895	.000*	.925	.000*	.966	.000*	.972	.000*
20%	.884	.000*	.905	.000*	.940	.000*	.968	.000*	.974	.000*
21%	.827	.000*	.885	.000*	.936	.000*	.968	.000*	.974	.000*
22%	.683	.001*	.777	.000*	.833	.000*	.960	.000*	.973	.000*
23%	.618	.006*	.678	.002*	.658	.001*	.933	.000*	.963	.000*
24%	.697	.001*	.736	.000*	.735	.000*	.901	.000*	.946	.000*
25%	.757	.000*	.775	.000*	.775	.000*	.877	.000*	.928	.000*
26%	.802	.000*	.808	.000*	.808	.000*	.860	.000*	.913	.000*
27%	.808	.000*	.808	.000*	.808	.000*	.835	.000*	.895	.000*
28%	.755	.000*	.756	.000*	.756	.000*	.790	.000*	.852	.000*
29%	.594	.009*	.594	.009*	.594	.009*	.588	.010*	.722	.000*
30%	.630	.005*	.630	.005*	.630	.005*	.620	.006*	.620	.006*

*Indicates statistically significant difference $p < .05$.

Table 5. Descriptive information of repeated measure one-way ANOVA for the standard deviation of COP positions

(Unit: mm)

Variables	Sensors	Mean ± S.D.	95% confidence levels		Post-hoc (Bonferroni)
			Lower	Upper	
M/L COP position	99 sensors[a]	2.79±0.10	2.58	3.00	a < b, c, d, e, f b < f, d, c
	4 sensors[b]	4.39±0.36	3.65	5.13	
	5 sensors[c]	4.88±0.33	4.20	5.55	
	6 sensors[d]	4.86±0.31	4.22	5.50	
	7 sensors[e]	4.67±0.33	3.99	5.34	
	8 sensors[f]	4.73±0.31	4.09	5.36	
Main effect	F (p)	F=49.428 (p=.000)			
	Effect size (η_p^2)	.630			
	Statistical power	1.000			
A/P COP position	99 sensors[a]	13.93±1.01	11.87	15.99	a < b, c, d, e, f f, e, d < b
	4 sensors[b]	23.72±3.02	17.55	29.90	
	5 sensors[c]	20.26±2.55	15.05	25.47	
	6 sensors[d]	19.20±2.35	14.39	24.01	
	7 sensors[e]	16.57±1.47	13.56	19.59	
	8 sensors[f]	16.43±1.23	13.93	18.94	
Main effect	F (p)	F=13.505 (p=.000)			
	Effect size (η_p^2)	.318			
	Statistical power	1.000			

4. Discussion

This study was conducted to optimize the number and positions of the pressure sensors required for smart shoes development using foot pressure sensors during gait analysis. To achieve the goal, a reliability analysis was carried out between the COP position estimated with 99 sensors' pressure values and those calculated with 4, 5, 6, 7, and 8 sensors. Using the analysis, this study aimed to present the optimal number and positions of the pressure sensors. Through the comparison of SD of COP position between each sensor condition, this study tried to analyze consistency of data.

First, upon the observation of the positions of the sensors used for the analysis, they were set to 8 regions of the foot, and the reliability and consistency were analyzed by estimating the COP positions with the pressure values of the corresponding sensors. The sensor positions were decided according to the order of foot pressure levels in walking based on the functional anatomical positions (Pappas et al., 2004; Bamberg et al., 2008; Hessert et al., 2005; Shu et al., 2010; Park et al., 2014; Shim et al., 2015; Lee et al., 2016). Precise positions were set on the basis of anthropometric structure and ratios of 26 bones constituting the foot (Isman and Isman, 1969; Davis, 1990; Dogan et al., 2007; Pietak et al., 2013). Based on the previous studies, the arrangement of the sensor positions based on the foot's functional anatomical positions during gait as human's basic mobility means, and can more precisely evaluate gait characteristics, which can be meaningful.

Second, during the stance phase in the walking process, COP positions showed a similar type with the general COP trajectory moving forward and inside of the foot. Upon looking at the reliability analysis result of A/P COP positions, a high positive correlation was shown between the COP position estimated with 99 sensors and those estimated with all the other sensors. The reason is judged to be the result of the sensor positions set at foot heel and hallux. According to the reliability analysis result on M/L COP positions, a statistically high positive correlation with statistically significant level was shown in the total stance phase from the moment when right heel strikes the ground to the moment when the end of the foot taking off the ground (1~30%) between the M/L positions estimated with 99 sensors and those estimated with 6, 7, and 8 sensors. Meanwhile, a low correlation was shown in the stance phase where right heel strikes the ground (1~4%) in terms of M/L COP positions estimated with 4 and 5 sensors, and a statistically significant result was not shown. Through this finding, it seems to be difficult to decide M/L COP positions at the moment when the heel strikes the ground during walking with 4 sensors, of which positions were set only at heel, and with 5 sensors, of which positions were set at the outside of calcaneus at the moment when the heel strikes the ground. Based on this result, the positions of LC and MT included in 6, 7, and 8 sensors appear to be important for the analysis of gait as shown in the study of Hessert et al. (2005) reporting that the pressures of the exterior of calcaneus at the heel and the interior of talus show big differences according to gait speed and type the moment when the heel strikes the ground. In addition, in a study of Shu et al. (2010) that estimated COP by attaching 6 sensors including at the 2 heel regions and compared with the force plate, the error rate was 0.5% and 2.2% at the moment the heel strikes the ground and taking off the ground, respectively. Therefore, it is presumed to be desirable to set pressure sensors by classifying M/L positions of the heel in order to enhance M/L COP position accuracy.

Third, this study calculated SD on position by each sensor to examine consistency of COP data between the conditions. Since SD means dispersion on the repeated results, consistency is determined to be higher, as the value of SD is smaller.

Upon looking at M/L COP positions, the consistency of the M/L COP position estimated with 99 sensors was highest, and the consistency of M/L COP positions estimated with 4, 5, 6, 7, and 8 sensors was smaller than that. Through the result that the consistency of M/L COP position estimated with 4 sensors was relatively higher than that estimated with 4, 5, and 8 sensors, it is conjectured to be more important selecting precise sensor positions rather than increasing the number of sensors in terms of M/L COP positions. Through further studies, there is a need to analyze the optimal positions of sensors for improvement of consistency on the M/L COP positions. The consistency of A/P COP position estimated that 99 sensors was the highest, and the consistency of A/P COP position estimated with 4 sensors was the lowest.

Lastly, the merit of this study is determined to be high in that the positions of sensors were decided on the basis of functional and anatomical standard considerations of gait characteristics compared with previous studies on the number and positions of pressure sensors, and in that the optimization of the number of sensors was conducted through reliability and consistency analyses with respect to the COP position estimated with 99 sensors. Therefore, this investigation would provide objective and meaningful information in order to monitor more accurate gait parameters such as the types and levels of activity using pressure sensors in the shoe.

5. Conclusion

Through smart shoes development, users' levels of exercise and activity amount can be measured, and accurate gait characteristics can be determined. This study was performed to optimize the number and positions of foot pressure sensors required for smart shoes development, with reliability and consistency analyses being undertaken. The conclusion of this study is as follows:

In determining and evaluating gait characteristics by using pressure sensors in the shoe, it is presumed to be desirable to arrange a minimum of 6 sensors based on functional anatomical basis from the reliability and consistency of the data. Thus, the study on the optimization of the number and positions of foot pressure sensors in the shoe is expected to positively contribute to developing more effective smart shoes.

Although this study was conducted at a certain gait speed targeting adult males, there is a need to carry out optimization on the number and positions of foot pressure sensors and gait speed variation for females in a further study.

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