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Evaluation of Thin Force Sensor Measurement and Determination of Plantar Pressure when Walking in Muddy Soil with Different Gumboots

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Abstract

Gumboots are used in agriculture in order to protect the feet from danger. However, some farmers do not wear, as they feel uncomfortable. In this study, Force Sensing Resistors (FSR) sensor was used as a measuring sensor, based on its better performance in terms of high repeatability and sensitivity. Verification of the sensor application in actual conditions was conducted with 4 different types of gumboot used in agricultural work. The peak pressures when walking in muddy soil were higher on average than when walking on a hard concrete surface. Gumboot types I and IV generated lower peak pressures than the other gumboots when walking on the hard concrete surface. On the other hand, gumboot types II and III resulted in the lowest and second lowest plantar pressure, respectively, while walking in muddy soil. The high hardness fraction on the heel, compared to other positions, in boot types II and III may have helped to reduce the average peak pressure during walking in muddy soil.

Keywords: Agricultural gumboots, FSR, repeatability, surface, peak pressure

Introduction

Gumboots, or Wellington boots, are useful and waterproof work boots that are made from rubber or polymer [1,2], for use in water, wetlands, arable soil, and wherever there is a dirty surface. The Ministry of Public Health of Thailand has campaigned for farmers to wear gumboots as personal protection equipment against hazardous chemical pesticides or soil and water diseases (e.g., Leptospirosis, Melioidosis). However, many farmers have rejected this suggestion, due to the difficulty in walking they have with these boots, and the discomfort they have experienced while working from the soil sticking to the boots.

Unlike other types of footwear, gumboots have a closed surface, and lack laces that could adjust the fit; consequently, ill-fitting dimensions may cause foot sores and blisters, in addition to causing walking difficulty [3]. The comfort parameters of boot wearing include impact force and plantar pressure [4,5].

Plantar pressure can be detected using commercial force measuring devices. However, since these instruments are so expensive, many researchers have studied the use of a low-cost, flexible force sensor (FlexiForce) that has high accuracy, sensitivity, and lower non-linearity [6,7], and have applied it in biomechanics for the measurement of grip force and plantar pressure in daily activity or for the diagnosis diabetes [8,9]. Force sensing resistors (FSR) are force sensors whose ideal properties are high repeatability, small size, light weight, high accuracy, low drift, and low cost, and with outputs that are independent of the ambient temperature and magnetic field, but have a non-linear response [10,11]. Non-linearity can be compensated for by a 4th or higher degree polynomial to obtain precise values [6,7].

The summation of static reaction loads acting on the foot is equal to the person's total weight. One foot supports the total weight when the other foot lifts up during walking. However, the actual dynamic loads acting on a foot are sometime greater than the total weight of the person. Sakai *et al*. [12] demonstrated the principle of a 60 kgf person producing an 80 kgf load by soil reaction on the left foot. Walking in muddy soil conditions, such as in a paddy field, requires the feet to support not only the human weight, but also the lift resistance force that occurs when lifting up the other foot. The lift resistance force may affect plantar pressure.

In this study, emphasis was placed on the validation of the appropriate thin force sensors to use as a measuring device for plantar pressure, and verification of the sensor was done by studying 4 different gumboots used in agricultural work.

Materials and methods

A force sensor, FlexiForce A201 (Tekscan Inc., USA) and a force-sensitive resistor (FSR 400, Interlink Electronics, USA) as shown in **Figure 1** were tested to determine the more suitable sensor for plantar pressure measurement under the study conditions. With initial electrical resistances of 1 and 10 MΩ, the FlexiForce and FSR sensors have 9.53 and 5.08 mm circular active-sensing areas, respectively.

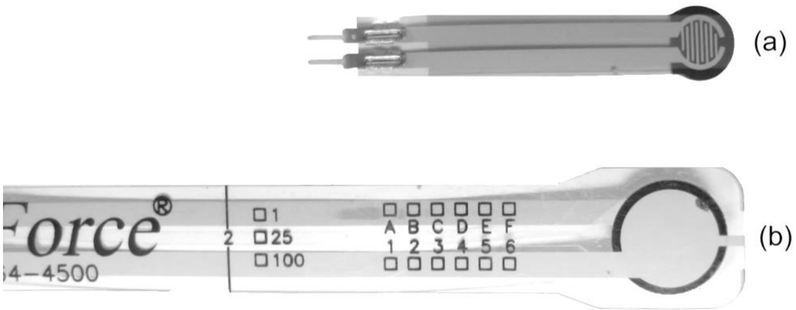

Figure 1 (a) Force sensing resistor (FSR 400) and (b) flexible force sensor (FlexiForce).

For static calibration, a dead weight method was applied. The sensor was laid between a flat indenter and an applied weight. The counterbalances were placed on the base of a sliding system. The output voltage of the sensor was converted using the NI USB-6009 data acquisition unit, and then data were processed and displayed using the LabVIEW software. Both the FSR 400 and FlexiForce units were tested in a pressure range of 0 - 1000 kPa. For the dynamic calibration, each type of sensor was installed and data was recorded in a similar manner to that used for the static procedure. The input cyclic loading was generated by a dynamic actuator with a duration of 0.6 s per cycle according to the speed of operation with a 2-wheel tractor [13,14].

Many researchers studying plantar pressure in human daily activity have reported that the pressure under the foot of a healthy subject will peak at 4 studied positions, i.e., the heel, the 1st metatarsal (M1), the 5th metatarsal (M5), and the big toe [15-17]. Therefore, in this study, the sensors were mounted at the 4 recommended positions on each boot, as shown in **Figure 2**. After that, the subject was careful to wear the gumboots to avoid damage to the wires, and did some practice walking before testing in order to develop sufficient skill to avoid inconsistent results due to wearer variability. Then, the subject stepped on the surfaces, the voltage signals that were detected by sensors were transmitted to the NI USB-6009, and the LabVIEW software was used for displaying, processing, and recording. The active sensing area of the sensor was covered with an epoxy dome to support the sensor contact point and which helped the force to be directly applied on the position [18]. According to Holleczek *et al*. [19], the subject wore socks to avoid the tape peeling off, which would allow the sensors to move.

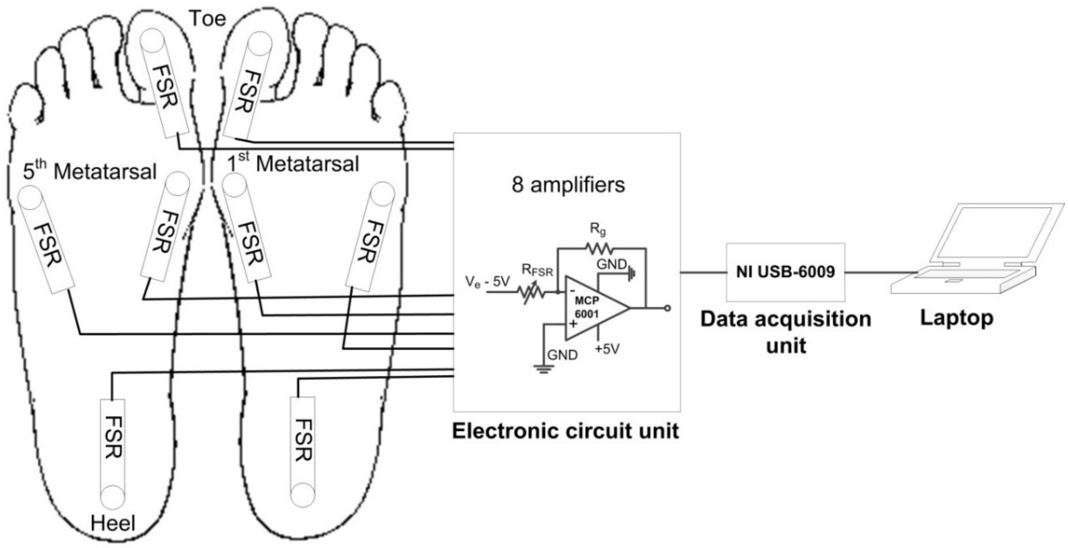

Figure 2 Schematic diagram of instrument and sensor locations.

In order to verify the use of the sensors for measuring plantar pressure in the actual operation, only one male without illness (34 years old, 85 kg weight, and 170 cm height) took part in the experiment, in order to avoid the effects of personal foot shape and walking pattern. Four pairs of gumboots, widely used in Thai farming, were chosen for this study. Gumboot type I is normally used in agricultural factories or clean rooms; type II is a general purpose boot, and types III and IV are popularly used in agricultural fields. The material hardness was measured using a Shore durometer type A (Desik); the details are listed in **Table 1**. The average hardness increased in the order of boot type I, II, III, and IV. Boot types I and IV had a low hardness fraction at the heel compared to other positions, while boot types II and III had the highest hardness fraction values at the heel (0.261 and 0.257, respectively).

Table 1 Material and hardness of boot types.

Boot type	Material	Average hardness				
		Toe	M1	M5	Heel	Mean
I	Elastomer	44.40^b	46.80^c	47.25^c	39.50^a	44.49^A
II	Polyurethane	50.70^b	48.30^a	48.20^a	51.95^c	49.79^B
III	Polyvinylchloride	62.80^b	62.50^b	60.40^a	64.10^c	62.45^C
IV	Polyvinylchloride	66.05^b	66.35^b	66.10^b	64.30^a	65.70^D

Remark: Values in the same row with the same lower case letter, and values in the "Mean" column with the same capital letter, are not significantly different by Duncan's multiple range test at a 95 % significance level.

Before testing, the subject trialed walking with a step length of 70 cm, with gait movement controlled by a metronome. The walking speeds were 1.6 [20] and 1.2 m/s [13,14] on a hard surface and muddy soil, respectively. Walkways 6 m long on the hard concrete surface and the muddy soil surface were prepared for the experimental test. The muddy soil consisted of a sandy clay loam (64 % sand, 9 % silt, and 27 % clay), having 60 % (db) moisture content, which replicated conditions commonly found in a paddy field.

Statistical analysis (ANOVA) was conducted by SPSS software, and post hoc test was performed using Bonferroni correction to estimate the differences of the hardness of footwear materials and plantar pressure in each position of both feet. Differences of means were separated by Duncan's New Multiple Range test. An acceptable significance level was 0.05.

Results and discussion

Force sensor calibration

The final fitted calibration curves (**Figure 3**) were fifth-order polynomial regression equations with high values for the coefficient of determination (R^2 = 0.9929 for FSR and R^2 = 0.9965 for FlexiForce). The fifth-order polynomial regression equation was also recommended in research work on the design and evaluation of a force sensing resistor by Thongudomporn *et al*. [21]. The FlexiForce sensor showed better linearity than the FSR, which was similar to the results reported by Lebosse *et al*. [22] and Komi *et al.* [23]. However, small differences could be observed from Lebosse *et al.* [22]. They found that, in terms of repeatability and hysteresis, the FSR and FlexiForce had very similar performances. In the current research, the FlexiForce was better in terms of hysteresis, whereas the FSR had better performance in terms of repeatability, as shown in **Table 2**. Repeatability was evaluated by computing the mean error of 3 applications with 22 different pressure loads.

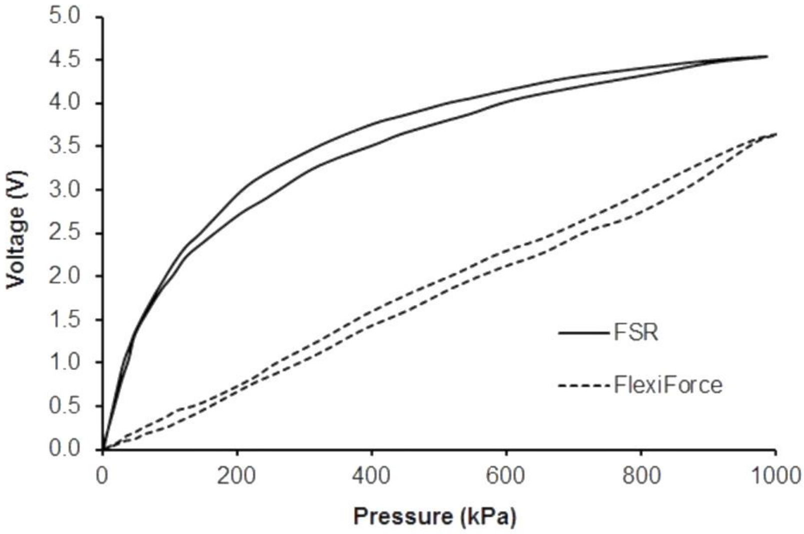

Figure 3 Static calibration of force sensing resistors.

Table 2 Static properties of force sensing resistors.

Sensor	Error of linearity (%)	Hysteresis (%)	Error of repeatability (%)	Drift (%)	Response time (µs)
FlexiForce	1.51	7.19	5.03	<5 [24]	<5 [24]
FSR	8.09	7.77	6.91	<5 [25]	<3 [25]

Figures 4 and **5** show the pressure responses of the FlexiForce and FSR sensors, respectively. The responding pressure had a very pronounced decrease, with successive loadings; the peak error declined 37.13 % over 10 cycles in the FlexiForce test, whereas it stayed relatively constant in the FSR test.

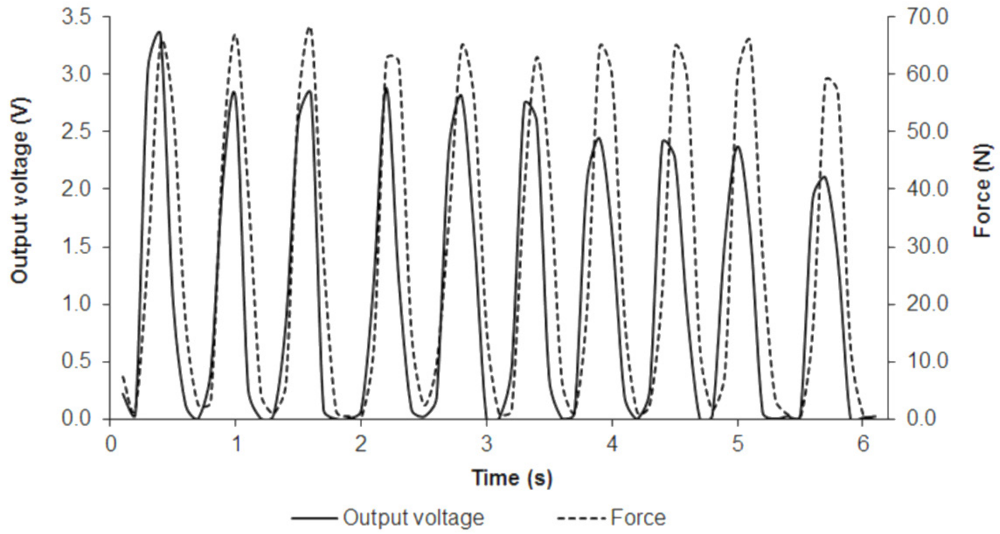

Figure 4 Variation of output voltage of FlexiForce with applied pressure during cycling loading.

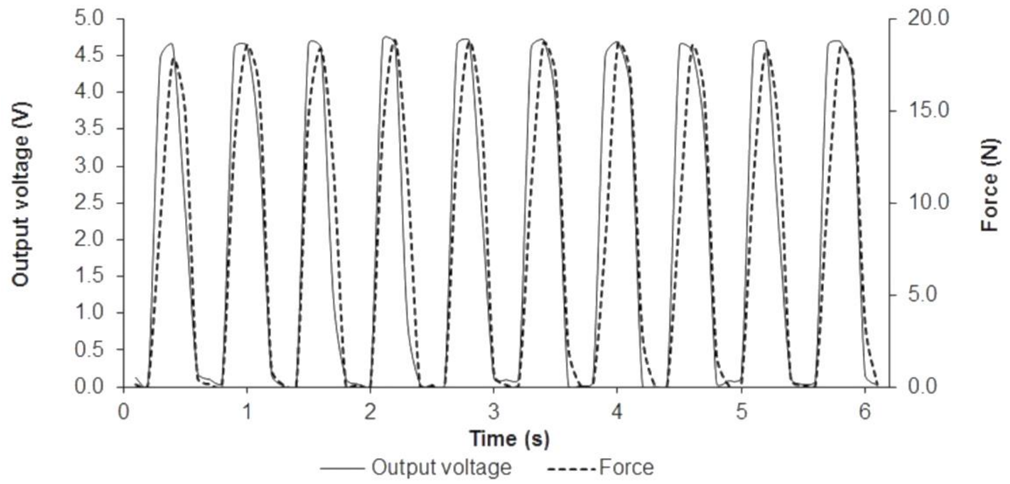

Figure 5 Variation of output voltage of FSR with applied pressure during cycling loading.

The FlexiForce showed higher linearity and low hysteresis, but had a slow response due to the decrease in output voltage repeatable forces (**Figure 4**). The FSR had less linearity and more hysteresis, but compensation could be provided using fourth or fifth degree polynomials for accuracy. Furthermore, it was better in terms of repeatability and sensitivity, and had a shorter response time. Thus, the FSR was selected for use in the research. All calibration equations of the FSR are in the general form of Eq. (1), and their corresponding coefficients are given in **Table 3**.

$$P = aV^5 + bV^4 + cV^3 + dV^2 + eV + C \quad (1)$$

where P is plantar pressure (kPa); a, b, c, d, and e are coefficients; V is the measured output voltage (V), and C is the intercept value.

Table 3 Coefficients in Eq. (1) for the FSR.

Sensor No.	Leg side	a	b	c	d	e	C
1	Left	-	2.8535	-14.837	27.028	32.896	10.333
2	Left	-	4.701	-27.814	55.605	8.7572	25.241
3	Left	1.9288	-18.471	69.367	-109.54	99.88	16.906
4	Left	-0.3961	6.4539	-25.369	36.278	42.041	18.273
5	Right	2.7643	-28.824	111.75	-179.51	159.85	-17.799
6	Right	1.6578	-15.511	58.984	-102.55	125.27	4.5013
7	Right	-	3.0034	-16.422	34.872	20.738	15.322
8	Right	-	3.0227	-19.673	58.307	-25.992	26.361

Plantar pressure

Walking in the muddy soil generated a significantly higher average peak plantar pressure than on the hard surface. The average peak pressures of the 4 positions were 280.46 and 183.28 kPa in the muddy soil and on the hard surface, respectively. The force used in lifting the gumboot might contribute to the higher value of the peak pressure of the gumboot on the muddy soil surface. There were differences in the average peak pressure on the left and the right boot. In normal walking on the hard surface, the test subject who was a right-handed person put more weight on the right gumboot, as the average peak pressure is 227.77 kPa, compared to 138.80 kPa for a left gumboot. However, it was interesting that, when walking in muddy soil, the average peak pressure of 301.51 kPa occurred on the left gumboot, which was more than the 259.41 kPa on the right gumboot. This may have been due to the subject putting additional force on the left foot, to be more stable when lifting the right foot up.

Table 4 Average peak plantar pressure during walking.

Surface type	Boot side	Boot type	Average peak pressure (kPa)				
			Toe	M1	M5	Heel	Mean
Hard	Left	I	115.84^{a}	81.45^{a}	103.21^{a}	126.655^{a}	106.79^{A}
		II	165.81^{b}	60.23^{a}	53.69^{a}	513.51^{c}	198.31^{B}
		III	125.03^{a}	56.79^{a}	106.32^{a}	241.47^{b}	132.40^{A}
		IV	113.90^{ab}	53.89^{a}	100.79^{a}	202.15^{b}	117.68^{A}
		mean±SD	130.14±24.27^{b}	63.09±12.51^{a}	91.00±24.98^{ab}	270.94±168.58^{c}	138.80±41.04
	Right	I	179.70^{b}	293.69^{c}	28.85^{a}	152.87^{b}	163.78^{A}
		II	260.24^{b}	214.39^{b}	25.07^{a}	715.66^{c}	303.84^{C}
		III	203.59^{b}	161.80^{b}	38.22^{a}	600.39^{c}	251.00^{B}
		IV	60.26^{a}	278.22^{b}	33.71^{a}	397.67^{c}	192.46^{A}
		mean±SD	175.95±84.20^{b}	237.03±60.77^{c}	31.46±5.73^{a}	466.65±247.05^{d}	227.77±62.36
	Both	I	147.77^{a}	187.57^{b}	66.03^{a}	139.76^{a}	135.28^{A}
		II	213.02^{b}	137.31^{ab}	39.38^{a}	614.58^{d}	251.07^{C}
		III	164.31^{ab}	109.30^{a}	72.27^{a}	420.93^{c}	191.70^{B}
		IV	87.08^{a}	166.06^{ab}	67.25^{a}	299.91^{b}	155.07^{A}
		mean±SD	153.05±51.97^{b}	150.06±34.09^{b}	61.23±14.82^{a}	368.79±200.28^{c}	183.28±50.88
Muddy soil	Left	I	111.23^{a}	224.40^{b}	174.07^{ab}	839.76^{c}	337.36^{B}
		II	107.19^{a}	113.36^{a}	138.48^{a}	620.84^{b}	244.97^{A}
		III	86.80^{a}	42.82^{a}	187.11^{b}	869.94^{c}	296.67^{B}
		IV	118.54^{a}	167.28^{a}	100.71^{a}	921.57^{b}	327.02^{B}
		mean±SD	105.94±13.60^{a}	136.96±77.43^{a}	150.09±38.81^{a}	813.03±132.50^{b}	301.51±41.46
	Right	I	41.31^{a}	824.96^{c}	105.00^{a}	423.57^{b}	348.71^{D}
		II	60.05^{a}	496.11^{b}	33.19^{a}	86.44^{a}	168.95^{A}
		III	55.32^{a}	664.13^{b}	64.55^{a}	138.57^{a}	230.65^{B}
		IV	54.84^{a}	492.98^{b}	41.63^{a}	567.92^{b}	289.34^{C}
		mean±SD	52.88±8.06^{a}	619.55±158.57^{b}	61.09±32.13^{a}	304.13±229.96^{b}	259.41±77.20
	Both	I	76.27^{a}	524.68^{b}	139.53^{b}	631.67^{c}	343.04^{D}
		II	83.62^{a}	304.74^{a}	85.83^{ab}	353.64^{a}	206.96^{A}
		III	71.06^{a}	353.48^{a}	125.83^{ab}	504.25^{b}	263.66^{B}
		IV	86.69^{a}	330.13^{a}	71.17^{a}	744.75^{d}	308.18^{C}
		mean±SD	79.41±7.08^{a}	378.26±99.62^{b}	105.59±32.34^{a}	558.58±168.28^{c}	280.46±58.79

Remark: Values in the same row with the same lower case letter, and values in the "Mean" column with the same capital letter, within the same block are not significantly different by Duncan's multiple range test at a 95 % significance level.

Table 4 shows the average peak plantar pressure during walking. The peak pressures among the 4 positions were significantly different, except for the toe and the 1st metatarsal on the hard surface, and also for the toe and the 5th metatarsal in the muddy soil. The highest (368.79 kPa) and the lowest (61.23 kPa) average peak pressures on the hard surface were recorded for the heel and the 5th metatarsal, respectively. On the other hand, the highest value was 558.58 kPa for the heel, and the lowest value was 79.41 kPa for the toe, in the muddy soil. For walking on the hard surface, the pressure profile was similar to the work of Nakanishi *et al*. [26], in which the pressure in the heel and toe positions was greater than in other places. When walking in muddy soil, the subject needed traction to move forward; therefore, greater stress occurred at the 1st metatarsal. This condition was similar to that occurring when a football player moves to "cut" the ball (cutting ball is an action that player uses inside of the foot to turn quickly to opposite direction), as traction force is important for rapid direction changing, and a high value under the 1st metatarsal was reported [27]. Taking into account the different sides, since the subject was a right-handed person, the heel of the right boot exerted more peak pressure (466.65 kPa) than the left boot (270.94 kPa) on the hard surface. However, the opposite trend was found in muddy soil (813.03 kPa on the left heel, and 304.12 kPa on the right heel). This might be because the right-handed subject tried to create stability when he lifted the right foot from muddy soil by putting additional force on the left heel. A comparison among gumboot types showed that, for both surface conditions, all types had significantly different values of average peak pressure, except for boot types I and IV on the hard surface. Boot type I induced a maximum average peak pressure on muddy soil (343.04 kPa), while boot type II did so on the hard surface (251.07 kPa). Focusing on the muddy soil surface, boot types II and III exerted lower average peak pressures compared to the other boot types. Moreover, while the other boot types showed greater average peak pressures in muddy soil than on the hard surface, boot type II inversely presented less peak pressure in muddy soil. The high hardness fraction on the heel, compared to other positions in boot types II and III, may have helped to reduce the average peak pressure while walking in muddy soil. From **Table 4**, peak pressures were generally highest at the heels of the gumboots. Gumboot types II and III had higher values of peak pressure at the heels, compared to the 2 other gumboots, on the hard surface, but had lower values in muddy soil. The heels of these 2 gumboot types, being harder than other positions as listed in **Table 1**, may have been able to bear more force than others on the hard surface whereas, in muddy soil, there were many more firm contact areas contributing to lower pressure at the heels.

Conclusions

The test results under static and dynamic conditions indicated that FlexiForce was better in terms of hysteresis, while FSR was better in terms of accuracy and sensitivity. Walking in muddy soil generated a significantly higher peak plantar pressure of 280.46 kPa compared to 183.28 kPa on the hard surface. The highest (368.79 kPa) and lowest (61.23 kPa) average peak pressures on the hard surface were measured at the heel and the 5th metatarsal, respectively. On the other hand, the highest value was 558.58 kPa at the heel, and the lowest value was 79.41 kPa at the toe, in muddy soil. Boot type I induced a maximum average peak pressure of 343.04 kPa on muddy soil, while boot type II was highest on the hard surface, at 251.07 kPa. On the muddy soil surface, boot types II and III exerted lower average peak pressures of 206.96 and 263.66 kPa, respectively, compared to the other boots. The high hardness fraction at the heel, compared to other positions, may have helped to reduce the average peak pressure while walking in muddy soil. In order to complete a comparative study of the 4 different agricultural gumboots, more subjects will be taken into the experiment in further study.

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