Original Article

Static and Dynamic Plantar Pressure and Normalized Plantar Pressure Characteristics among Children, Adults, and the Elderly

Poonyanat Nualon PT, PhD[1], Plaiwan Suttanon PT, PhD[2], Vinitha Puengtanom MSc[1], Piyasiri Ngamsangiam PT, MSc[2,3], Sudarat Apibantaweesakul PT, MSc[1,4]

[1] Department of Sports Science and Sports Development, Faculty of Allied Health Sciences, Thammasat University, Pathum Thani, Thailand

[2] Department of Physical Therapy, Faculty of Allied Health Sciences, Thammasat University, Pathum Thani, Thailand

[3] Department of Physical Medicine and Rehabilitation (Physical Therapy), Lerdsin Hospital, Bangkok, Thailand

[4] Graduate School of Sport Sciences, Waseda University, Saitama 359-1192, Japan

Background: A better understanding of plantar pressure while standing and walking would help in improving balance and gait performance across different age ranges.

Objective: To clarify the differences of plantar pressure while standing and walking among children, adults, and the elderly.

Materials and Methods: Fifty-three participants including eleven aged 3 to 8 years, thirty aged 20 to 40 years, and twelve aged 60 to 90 years were included in the present study. Plantar pressure and related parameters while quiet standing and walking with self-selected speed were assessed.

Results: In static plantar pressure, no significant differences were observed of mean different pressure and mean different contact area between dominant and non-dominant limbs among the three groups, while center of pressure (COP) displacement was shown as significantly greater between children and adults ($p<0.05$). For dynamic plantar pressure, no significant differences in COP velocity were found among the three groups. The elderly showed significant lower normalized maximum plantar pressure in areas of the second and third metatarsal, and internal heel compared with the young adults ($p<0.05$). Additionally, normalized maximum plantar pressures among children seemed to differ from adults.

Conclusion: Plantar pressure characteristics could indicate that children develop gait ability in braking and propulsion phases with greater heel and toe function, while the ability of braking and propulsion declined with aging. These could reflect balance ability while standing or walking.

Keywords: Foot pressure; Children; Elderly; Normalization

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The plantar pressure measurement is commonly used in the clinical evaluation of the foot and provides insight into the plantar loading characteristics during functional activities such as standing, walking, and running[1,2]. The distribution of plantar pressure has frequently been measured to understand the changes in pressure applied to the foot, changes in the center of pressure, and changes in gait pattern in the different age groups[3-5]. As the chronological age increases, the human body goes through a period of transformations that generates decline in some physical activities, such as standing and walking. In the childhood stages, the musculoskeletal system experiences spectacular development of skeletal and muscular structures. It is subject to compressive and tensile stresses that are important for normal development of the bone and muscle morphology for loading requirements in the next developmental stages[6]. The mature musculoskeletal system in adults has shown from data of plantar pressure assessment in the normal foot that the greatest area of foot pressure distribution is in the heel, forefoot lateral, forefoot medial, and midfoot in rank order[7]. Age-related anatomical and physiological changes in foot bone and ligament structure affect plantar pressure distribution during walking. A previous study investigated the variables of foot pressure distribution between young and older subjects. All variables of the anatomical region in

Correspondence to:

Apibantaweesakul S.

Department of Sports Science and Sports Development, Faculty of Allied Health Sciences, Thammasat University, Pathum Thani 12121, Thailand.

Phone: +66-2-9869213 ext. 7239, **Fax**: +66-2-9869055

Email: sudarat.thamm@gmail.com

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the elderly were lower than in adults[1]. The present study was conducted with a small sample size and the foot arch in static posture was not evaluated[1]. It is important to note that pressure distribution during standing could indicate the foot type characteristics. Few studies revealed the foot type related to pressure distribution when walking in young children. In addition, the knowledge of static and dynamic foot pressure distribution characteristics with body dimension consideration among development and degenerative change periods remains limited. A better understanding of static and dynamic foot pressure distribution would assist in explaining foot characteristics in each age period, and this could also imply to changes in balance performance of each age group. The present study aimed to investigate plantar pressure distribution during standing and walking among the three different age groups. The authors hypothesized that characteristics of plantar pressure distribution during standing and walking might be different among the three different age groups.

Materials and Methods

Study design and setting

The present study employed an observational descriptive design conducted at Thammasat University. The data were collected between February and May 2020.

Participants

Participants consisted of 53 volunteers with eleven aged 3 to 8 years old, thirty aged 20 to 40 years old and twelve 60 to 90 years old, as shown in Table 1. All participants recruited were found to be healthy. The exclusion criteria included having 1) a recent history of lower extremity trauma such as sprain, tendinitis, fractures, or surgery, 2) neurologic, orthopedic, or neuromuscular condition(s) that would affect mobility and function in daily living, 3) abnormal body mass index. Ethics approval was obtained from the Human Ethics Committee, Thammasat University (COA No.098/2562). All participants and guardians signed informed consent before recruitment in the present study.

The sample size was calculated using G power (G*power version 3.1.9.2) based on the related study[8] measured ground reaction force and spatiotemporal parameters during normal walking (effect size=0.27, α error probability=0.05, and power=0.95).

Experimental protocols and data acquisition

A pressure distribution dataset was collected using the FootWork Pro pressure plate (Am CUBE, Inc., France) with dimensions 575×450×25 mm, rubber coating and 2,704 calibrated capacitive sensors at two sensors/cm^2, and setting the sampling frequency at 100 Hz. For familiarization purposes, participants performed one practice trial for both static and dynamic tests on the pressure plate to ensure that they were comfortable with the experimental procedure. Two trials were conducted, and the mean of the two completed trials per foot was used for the data analyses in the present study. For the static test, participants were asked to stand on the platform, barefoot, in upright posture, lower limbs extended, and their arms relaxed by their side. They were instructed to look forward at a fixed point for 10 seconds. During the dynamic test, participants were instructed to walk barefoot at normal speed over the pressure plate, which was five meters long. For each trial, the participant's right and left foot strike was measured on the plate.

Data analysis

All data were analyzed using the FootWork Pro Software. The variables in static protocols included the mean pressure (kPa), contact area (cm^2) and ellipse area at the center of pressure (cm^2). In dynamic protocols, the pressure area under the feet was automatically divided in eight anatomical regions. Feet regions included the hallux (H), other toes (OT), the first metatarsal (M1), the second to the third metatarsal (M2/3), the fourth to the fifth metatarsal (M4/5), middle foot (MF), internal heel (IH), and external heel (EH)[9-11].

Statistical analysis

Data analysis employed the IBM SPSS Statistics for Windows, version 23.0 (IBM Corp., Armonk, NY, USA). Non-parametric analysis was used. All parameters were statistically described in median and 25th to 75th percentile. Kruskal-Wallis test was used to compare the plantar pressure distribution among the group age factors, with a post hoc test using Mann-Whitney test with Bonferroni correction to further analyze the results. The level of significance was set as p-value less than 0.05 for all the tests.

Results

The characteristics of participants are presented in Table 1. Data were shown in median and 25th to 75th percentile.

Table 2 summarizes the participants' mean pressure, and the contact areas of foot on the

Table 1. Participant's characteristics

Characteristics	Children (n=11); median (25th to 75th)	Adults (n=30); median (25th to 75th)	Elderly (n=12); median (25th to 75th)
Sex: male/female	5/6	15/15	3/9
Age (years)	4.00 (4.00 to 6.00)	29.50 (22.00 to 35.00)	70.50 (68.00 to 75.50)
Weight (kg)	18.50 (15.10 to 19.70)	57.50 (54.00 to 65.00)	53.13 (50.85 to 56.70)
Height (cm)	107.00 (102.00 to 118.00)	164.50 (160.00 to 170.00)	158.50 (153.00 to 161.00)
BMI (kg/m^2)	15.20 (13.52 to 17.59)	21.48 (20.17 to 23.05)	21.64 (20.50 to 22.99)

BMI=body mass index

Table 2. Static plantar pressure analysis among three different age groups

Parameters	Side	Children (n=11); median (25th to 75th)	Adults (n=30); median (25th to 75th)	Elderly (n=12); median (25th to 75th)	p-value
Mean pressure (kPa)	DL	9.63 (9.14 to 11.29)	17.62 (15.87 to 19.77)	16.03 (13.49 to 19.07)	a, b
	NDL	14.03 (10.22 to 14.60)	20.92 (17.99 to 23.96)	15.58 (14.69 to 17.73)	a, c
	MD	1.85 (1.69 to 5.12)	3.41 (0.94 to 5.04)	1.89 (0.52 to 3.74)	0.304
Contact area (cm^2)	DL	26.10 (24.07 to 30.16)	56.26 (50.46 to 66.12)	54.52 (49.30 to 72.79)	a, b
	NDL	19.145 (15.66 to 25.52)	54.81 (48.14 to 63.80)	51.04 (44.08 to 63.80)	a, b
	MD	9.86 (2.32 to 12.18)	6.38 (2.90 to 10.59)	6.67 (2.90 to 8.56)	0.544
COP displacement					
Ellipse area (cm^2)		10.80 (9.95 to 18.63)	2.60 (1.62 to 4.39)	5.97 (2.76 to 8.37)	a

COP=center of pressure; DL=dominant leg; NDL=non-dominant leg; MD=mean difference between DL and NDL

a: Significant difference between children and adults ($p<0.05$); b: Significant difference between children and elderly ($p<0.05$); c: Significant difference between adults and elderly ($p<0.05$)

dominant and non-dominant sides and center of pressure displacement during standing. The data of mean pressure and contact area on the dominant side revealed significant differences ($p<0.05$) between children and adults and between children and the elderly. On the non-dominant side, the results of mean pressure showed significant difference in the two groups between children and adults and between adults and the elderly ($p<0.05$). In addition, the data of the contact area indicated significant difference in the two groups between children and adults and between children and the elderly ($p<0.05$). The data of side differences showed no significant difference in mean pressure and contact area among the three ages group. From the result of COP displacement, the ellipse area showed significant difference between children and adults ($p<0.05$).

Maximum COP velocity did not significantly differ between the three groups, while step duration was significantly lower among children than adults and the elderly (Table 3). Table 3 also shows the data of the total contact area of the foot, and the maximal pressure in eight subareas of the foot (N/cm²) and normalized data by body weight (%BW/cm²) in all groups. The results of the total contact area showed the significant difference in the two groups, between children and adults and between children and the elderly ($p<0.05$). The maximum pressure of H, M1, M2/3, M4/5, and the EH subarea foot revealed significant differences between children and adults ($p<0.05$). In addition to the maximum pressure of the M2/3, IH, and EH subarea of the foot, the data showed significant difference between adults and the elderly ($p<0.05$), while the differences between the OT and MF subarea did not significantly differ. The present study showed the maximum pressure normalized by body weight in all group ages. The data revealed the EH subarea of the foot exhibited significant difference between children and adults, and between children and the elderly ($p<0.05$). Additionally, the data of maximum pressure of the IH significantly differed between children and the elderly and between adults and the elderly ($p<0.05$); while the M2/3 subarea revealed significant difference between adults and the elderly ($p<0.05$). Regarding the normalized data of maximum pressure in the subarea of H, OT, M1, M4/5, and MF, the data showed no significant difference in all age groups.

Table 3. Dynamic plantar pressure analysis among three different age groups

Parameters	Children (n=9); median (25th to 75th)	Adults (n=30); median (25th to 75th)	Elderly (n=12); median (25th to 75th)	p-value
Step duration (ms)	480.00 (320.00 to 480.00)	720.00 (652.50 to 752.50)	820.00 (790.00 to 1,490.00)	a, b
Total contact area (cm²)	50.43 (41.76 to 53.94)	83.23 (73.08 to 95.70)	83.23 (77.72 to 92.51)	a, b
Maximum COP velocity (mm/s)	1,234.71 (1,091.59 to 1,375.75)	1,576.07 (1,065.77 to 2,076.02)	1,518.64 (1,200.43 to 2,760.65)	0.288
Maximum pressure (N/cm²)				
Hallux	9.10 (3.65 to 12.00)	23.60 (11.95 to 29.85)	18.75 (7.75 to 26.03)	a
Other toes	5.70 (2.25 to 16.25)	15.2 (7.00 to 20.03)	8.55 (4.53 to 14.30)	0.129
M1	5.70 (1.25 to 10.70)	21.45 (16.10 to 25.75)	13.45 (10.98 to 23.23)	a
M2/3	9.10 (1.40 to 15.65)	27.5 (24.35 to 33.30)	18.25 (12.05 to 27.95)	a, c
M4/5	11.30 (3.75 to 17.70)	22.15 (17.68 to 30.55)	17.50 (12.00 to 30.75)	a
Middle foot	2.50 (0.00 to 5.25)	2.90 (0.00 to 7.45)	4.60 (3.10 to 11.40)	0.196
Internal heel	16.90 (9.70 to 26.60)	23.10 (18.83 to 26.75)	16.50 (12.00 to 18.90)	c
External heel	14.40 (9.25 to 19.85)	22.6 (18.90 to 25.55)	17.35 (13.02 to 1928)	a, c
Normalized maximum pressure (%BW/cm²)				
Hallux	6.10 (1.68 to 6.65)	4.25 (2.15 to 5.51)	3.54 (1.42 to 4.50)	0.288
Other toes	3.82 (1.03 to 10.20)	2.67 (1.15 to 3.57)	1.55 (0.81 to 2.85)	0.129
M1	3.00 (0.75 to 5.10)	3.52 (2.86 to 4.61)	2.53 (1.97 to 4.11)	0.172
M2/3	4.30 (0.84 to 6.87)	4.99 (4.26 to 6.03)	3.55 (2.30 to 4.09)	c
M4/5	7.22 (2.11 to 8.19)	4.03 (2.72 to 4.88)	3.04 (2.24 to 5.92)	0.434
Middle foot	1.15 (0.00 to 2.76)	0.53 (0.00 to 1.20)	0.75 (0.58 to 2.09)	0.370
Internal heel	8.97 (3.90 to 17.11)	3.70 (3.25 to 4.96)	3.09 (2.28 to 3.52)	b, c
External heel	7.22 (4.62 to 11.23)	3.66 (3.27 to 4.74)	3.22 (2.53 to 3.52)	a, b

COP=center of pressure; M1=1st metatarsal; M2/3=2nd and 3rd metatarsal; M4/5=4th and 5th metatarsal

a: Significant difference between children and adults ($p<0.05$); b: Significant difference between children and the elderly ($p<0.05$); c: Significant difference between adults and the elderly ($p<0.05$)

Discussion

In the present study, the authors investigated both static and dynamic barefoot plantar pressure characteristics in the three different age groups. Weight bearing between dominant and non-dominant limbs discussed in static plantar pressure section referred to mean different plantar pressure, mean different contact area, and COP displacement. Moreover, the pattern of plantar pressure during normal walking was observed in three different age ranges, determining specific pattern in each period. However, the related studies reported that body mass affected plantar pressure[12,13]. Therefore, the present study conducted the normalized plantar pressure to compare the three different age groups.

Static plantar pressure distribution

Although a previous study evaluated static plantar pressure in specific area under the foot[14], asymmetry weight-bearing could indicate by a greater contact surface area as an indicator of fall risk[15]. Therefore, the results of the present study could point out the symmetry of mean plantar pressure and contact area in the three age groups. Interestingly, greater contact areas were found among children, the elderly, and adults in the rank. These may represent a high risk of falls while standing in children and elderly groups. These also corresponded to COP displacement, in particular the difference between children and adults. A related systematic review reported that COP parameters during bipedal quiet standing can constitute a falls risk predictor that could create better models for falls prevention care[16]. On the other hand, when considering mean plantar pressure, the highest value was found among adults. One explanation was the influence of body weight[12,13]. Moreover, the weight status among children could also affect the plantar load distribution and their foot structure changes due to the growth and development process[1]. Concerning contact area results, the dominant side showed greater value than the non-dominant side in all three age groups. Regarding foot dominance, it may be possible that the foot arch is lower when compared with the non-dominant foot where the dominance side plays a role to support the body during the required task[17]. However, children showed greater mean different contact area between the two sides than those in the adult and elderly groups. These may relate to foot development including both structure and function, and stability control development in terms of COP displacement.

Dynamic plantar pressure distribution

Maximum COP velocity showed no significant difference among the three groups. However, the 25th to 75th percentile COP velocity was higher among the elderly. Related studies supported that COP velocity increased with age and history of falls[18,19], while step duration among children was significantly lower compared with adult and elderly groups. Additionally, this depended on differences in foot dimension. Normalized spatiotemporal parameters would be recommended for further study. The results of studies investigating dynamic plantar pressure distribution among adults and the elderly showed that all eight areas had higher maximum pressure than those of children except the IH among the elderly. This indicated that age is a factor influencing plantar pressure distribution and this corresponded to a related study[5]. Findings of the present study showed the high maximum pressure in the heel of the stance phase supported the fact that the COP in normal walking started from the heel. Then gradually the COP moved from the heel to the toe through the midfoot and metatarsal region. Related studies have shown the maximum pressure is unevenly distributed under the foot region among healthy adults[10,20,21] and older individuals[9]. According to the findings of the toe regions, recent studies have reported the maximum pressure in H was higher than that of the OT[1,21,22]. However, the difference in body dimensions, particularly body weight would influence plantar pressure while walking. Therefore, the present study aimed to compare normalized plantar pressure in different age groups to clarify the changes of plantar pressure while walking. Among the elderly, all areas of the foot exhibited less pressure than that of children and adults showing a similar pattern with the non-normalization method. IH and M2/3 regions were significantly lower among elderly than those of adults. This implies that the elderly bear weight on the lateral foot especially at heel strike and push-off phases. These results also agree with one related study that concluded lateralized foot pressure and decreased propulsion might affect walking and balance abilities[1]. The present study could expand the possible relation of fall risk in which the lower heel pressure especially medial region may affect braking ability and balancing at the heel strike phase either slipping backward or sideward. Considering normalized plantar pressure among children, greater maximal pressure was observed particularly in the heel, M4/5, OT, and hallux, and lesser in M1 and M2/3 compared with adults. At heel strike and toe-off, children presented greater pressure during their walking. This result agreed with a related study that children attempted to stabilize the ankle, while adults can brake and propel the ankle[17]. At late midstance, higher plantar pressure in M4/5 may correspond with gait pattern including maximum medial or lateral force and stride width[23,24]. In addition, the propulsion ability among children seems to be developing with the present study's findings indicating lower pressure in M2/3 and greater in H and OT compared with adults. One explanation is H and toes provide the strategy to control walking ability including propulsive force and balance function. A related study supported that metatarsophalangeal joint stabilization configuration may also relate to the pre-swing phase among children[25]. The development of new walking in younger children can be presented in three roll-off patterns including initial heel strike, plantar contact, and toe walking in which the initial heel strike becomes the most important roll-off pattern under the foot with increasing walking experience[26]. Although the present study's child participants illustrated an initial heel strike pattern similar to that found in adult and elderly groups, the development of the roll-off pattern might affect H and toe pressure. These could improve stability for younger children following a forward shifting of the load and allowing more muscular control[26,27]. Additionally, push-off under H was more essential in new walkers compared with adults[28]. Moreover, types of foot also influence plantar pressure and balance ability[9]. Higher normalized pressure in the MF area was found among children than among adults and elderly group in the present study. This agreed with a related study[26] that may be associated with an incomplete development of foot arch components[28].

Related research has reported the numerous factors that influence plantar pressure including walking speed[29,30], shoe condition[29], footwear type[31], foot deformity[29], and dominant or non-dominant sides of the foot[15]. A study by Burnfield et al reported that plantar pressure increased at faster walking speeds and when walking barefoot[29,30]. Wearing minimal shoes was found to remain stable during standing and revealed faster functional mobility when compared with conventional shoes[31]. Additionally, foot deformity such as hallux valgus where metatarsal-phalangeal angle is 20° or greater, when walking barefoot exhibited low mean peak pressure under the great toe than that of participants presenting hallux valgus angle of less than 20°[29].

The present study has a few limitations. Firstly, even though the current findings were obtained from a larger number of subjects compared to the previous study[1] among the three age groups, an increased sample size for each age group would maximize the study generalizability. Further studies should implement a larger population for each age group with a normal gait pattern and full range of motion in plantar flexion and dorsiflexion. Secondly, the present study was designed using self-selected walking speed in barefoot condition on the dominant side to decreased influencing factors. However, walking speed in the present study was doubtful due to the different age groups and lacking speed report. This limitation could be mitigated with appropriate normalization methods in the future study. Finally, the spatiotemporal and biomechanical parameters such as step length, step width, and lower extremity joint angle should be observed as related variables or confounding factors.

The clinical implications of the present study relate to potential differences in plantar pressure distribution under IH and second and third metatarsal subareas in elderly could expand the possible relation of fall risk in which the lower heel pressure especially medial region could influence braking ability and balancing at the heel strike phase.

Conclusion

The specific characteristics of static and dynamic plantar pressure distribution revealed for each age period could reflect balance ability during either standing or walking. These could indicate that children present gait ability in braking and propulsion phases with greater heel and toe function, however, braking and propulsion ability decline with increased age.

What is already known on this topic?

Plantar pressure characteristics were evaluated as either static or dynamic in children, adults, and elderly separately with specific condition. Knowledge of the changes in plantar pressure distribution and characteristics across ages remain limited.

What this study adds?

This current study provided information of plantar pressure distribution and characteristics across ages as children, adults, and elderly, with appropriate normalization method during static and dynamic in which reflected specific pattern and influenced changes in each age period.

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Conflicts of interest

The authors have each completed and submitted an International Committee for Medical Journal Editors Uniform Disclosure Form for Potential Conflicts of Interest. None of the authors disclose any conflict of interest.

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