Journal of Rehabilitation Sciences and Research

Journal Home Page: jrsr.sums.ac.ir

Original Article

Plantar Pressure Distribution in People with Stroke and Association with Functional Mobility

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ARTICLE INFO

Article History:
Received: 23/03/2019
Revised: 27/05/2019
Accepted: 29/05/2019

Keywords:
Stroke
Foot
Plantar pressure
Mobility

Please cite this article as: Forghany S, Nester CJ, Tyson SF, Preece S, Jones RK. Plantar Pressure Distribution in People with Stroke and Association with Functional Mobility. JRSR. 2019;6(2):80-85. doi: 10.30476/JRSR.2019.81232.

ABSTRACT

Background: People with stroke often suffer abnormal foot posture including structural and movement deficiencies in the intrinsic foot segments on the affected side, which are associated with limitation in mobility. As part of a programme of research examining foot and ankle biomechanics after stroke, we investigated plantar pressure distribution under the affected foot of people with stroke and the relationship with functional mobility.

Methods: Plantar pressure distribution was investigated while standing and walking on the affected side of twenty stroke and fifteen healthy sex and age-matched participants, using a Medilogic platform system at a frequency of 20 HZ. Functional mobility in real life was measured using the Walking Handicap Scale.

Results: While standing, people with stroke bore greater pressure on the affected side through the lateral heel and lesser toes ($P<0.01$) and less at the medial (MP1) and central forefoot (MP23) areas ($P<0.05$) than healthy controls. During walking, more pressure was taken through the heel area, especially the medial heel and less through the medial and central forefoot of the affected foot of people with stroke compared to healthy controls.

The logistic regression model revealed that stroke participants who took greater pressure on the medial heel while walking (odds ratio=1.11, $P<0.05$) had more limited functional mobility (i.e. were more likely to be household walkers) than those who did not. While standing, none of the standing plantar pressure variables significantly contributed to the model.

Conclusion: The plantar pressure distribution differs significantly between the affected foot of people with stroke and healthy controls. Abnormal plantar pressure distribution while walking, but not while standing, is a significant contributor to limited functional mobility post stroke.

Introduction

Stroke is the leading cause of adult disability, impairs mobility and, with the ageing population, its incidence is expected to rise in the future [1, 2]. Regaining the ability to walk independently and safely is a priority for many stoke survivors and is considered a primary goal in stroke rehabilitation [3]. Since the foot determines the interaction between the lower limb and ground, its function is fundamental to how walking is achieved. It is already known that stroke survivors suffer abnormal foot posture with similar frequencies of supination (13%) and pronation (16%) abnormalities [4]. They also show structural and foot movement deficiencies on the affected side, such as reduced range of motion across most segments and planes, increased pronation

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and reduced supination [5]. Most importantly, some of the abnormalities on the weak side, such as supination or pronation foot posture, a less plantarflexed or less inverted rearfoot at toe off, and a less adducted rearfoot in late stance, have already been shown to be associated with limited walking ability [4, 5].

Plantar pressure distribution is fundamental to understanding how load is transferred in the weight bearing limb and to limb motion [6-9]. Whilst foot posture and kinematics have been shown to influence mobility of stroke survivors [4, 5], these associations have not been explored using plantar pressure data. However, the few studies of plantar pressure distribution in people with stroke have shown differences in the pattern and magnitude of plantar pressure under the affected foot compared with healthy participants [8, 10, 11]. Meyring et al found lower peak pressures at most anatomical sites on the affected foot, and a shift in load from the lateral to the medial forefoot [11]. However, this study involved a very heterogeneous sample, with hemiparesis arising from a variety of different causes. Compared to age- and gender-matched controls, Feys et al reported greater medial heel and midfoot loading and a more forward location of the center of force at initial contact in cases of stroke, indicating a less pronounced heel strike on the affected side [10]. The results of these plantar pressure studies are, to some extent, in accordance with the results of the only reported multi-segmental foot kinematics study showing that people with stroke had reduced range of motion across most segments and planes, a more everted rear foot, slightly more inverted forefoot and a deficient rocker function [5] To date, however, the literature has generally focused on how separate aspects of foot are affected e.g. kinematics and posture [4, 5], or plantar pressure [10, 11], but not how changes may inter-relate.

Since plantar loads are integral to the loads that create foot motion, there should be an association between plantar pressure and functional mobility. The lack of objective information on foot pressure in stroke and failure to explain how pressure may affect the reported changes in foot motion and posture could lead to interventions such as footwear or orthoses being underutilized, or indeed misused. Explaining whether and how features, such as plantar pressure, associate with functional mobility in stroke might assist in the development of interventions to improve foot and ankle function which, in turn, could increase function and quality of life. As part of a programme of research examining foot and ankle biomechanics after stroke, we investigated plantar pressure distribution under the affected foot of people with stroke and the relationship with functional mobility.

Methods

Ethical approval was obtained from the university and NHS's Central Office for Research Ethics Committees (COREC). People with stroke were recruited if they were at least one week after stroke, able to give informed consent, able to stand on their own (holding on to something if necessary), well enough to participate (as judged by the participant and the clinical team) and able to walk independently (barefoot with or without an assistive device for at least 10 meters). They were excluded if they had medically unfit to undergo testing, history of a foot and ankle injury prior to stroke (sufficient to limit mobility pre-morbidly) or post stroke lower limb surgery, Botox injection into lower leg during past three months or another mobility-limiting condition (such as dementia or Parkinson disease).

Twenty stroke participants (7 men and 13 women, age 65.0±10.2 years, height 1.65±0.1 meters, weight 73.2±18.2 kilograms and median time after stroke 6.9 months, IQR: 10.4 months) were recruited from in and out-patient stroke services of the local hospital and a stroke support group . Of these 17 had suffered an ischemic stroke (3 hemorrhagic), which affected the right side for 8 participants and left for 12. All were able to walk barefoot independently for at least 10 meters without any assistive device. Fifteen healthy age-matched participants, (10 men and 5 women, age 67.1±8.6 years, height 1.64±0.09 meters and weight 72.6±8.5 kilograms, twenty side-matched feet) were also recruited. There were no significant differences in age (P=0.52), height (P=0.90) or weight (P=0.91) between the two groups. Informed consent was obtained for all participants.

The study took place at the university research gait lab of The University of Salford. Concurrent with foot kinematic data previously reported [5], plantar pressure distribution was measured while barefoot standing and walking (at a self-selected speed) over a Medilogic platform system (T&T Medilogic, Berlin, Germany). The 480x480mm pressure platform was mounted flush to a walkway comprised 4096 5mmx6mm sensors in a 64x64 matrix (1.77 sensors per cm^2). The plantar pressures were measured at a frequency of 20Hz (maximum permitted) which was felt adequate for the slow walking speed found in stroke and older people [12]. The pressure measurement system was calibrated at the start of study and after six months by the manufacturer.

A minimum of three standing trials (20 seconds) and ten walking trials were collected, respectively, with adequate periods of rest between each trial. During standing trials, participants placed their feet in a relaxed self-selected posture. As stroke participants have problems initiating and terminating gait, participants initiated gait two step lengths before the pressure platform and continued gait two meters after it.

To assess the plantar pressure distribution, the plantar aspect of the foot was divided into eight functionally relevant regions; medial and lateral rearfoot, midfoot, medial, central and lateral forefoot, hallux and lesser toes (Figure 1). The rearfoot region was 31% of foot length, the midfoot region was 19% and the forefoot region was 50% of foot length [13, 14]. The forefoot was divided into two segments; the metatarsal and toe areas by visual inspection. The medial-lateral division of rearfoot was determined manually according to the visually estimated

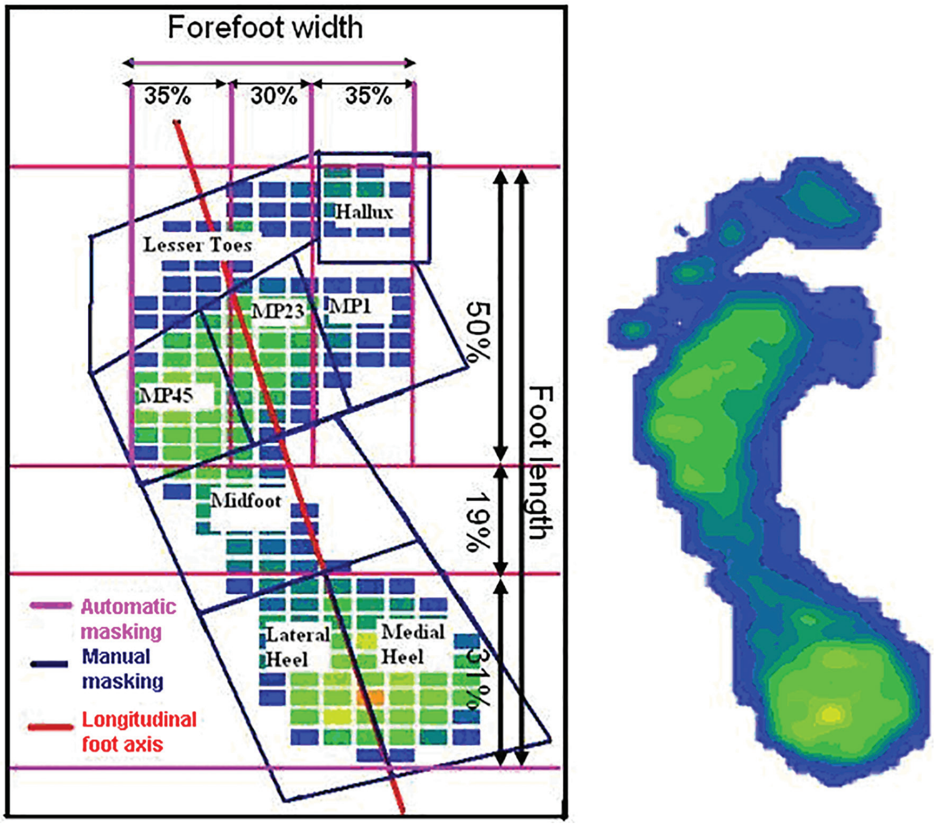

Figure 1: Masking of plantar pressure image into eight segments. Medial and Lateral heel, Midfoot, Medial forefoot (MP1), Central forefoot (MP23), Lateral forefoot (MP45), Hallux and Lesser toes.

longitudinal axis of foot between the middle of the heel and second metatarsal.

The metatarsal area was automatically divided into three medial/lateral areas including medial (first metatarsal head), central (second and third metatarsal heads) and lateral forefoot (fourth and fifth metatarsal heads). The medial region was 35% of forefoot width, the central region was 30% and the lateral region was 35% [15]. The toe area was divided manually into two areas; hallux and lesser toes. Figure 1 shows automatic and manual masking of plantar pressure image into eight segments.

Normalized average pressure-time integral (NAPTI) was used in the present study [16, 17]. The average pressure in each mask was plotted as the function of stance time and then integrated to give a measure which comprised both magnitude and time. To account for foot size, body weight, asymmetrical weight bearing and spatio-temporal variables, the data were normalized [16, 17]. The average pressure-time integral of the total foot plantar surface was calculated and the values for each mask were normalized to this value. This produced a normalized average pressure-time integral (NAPTI) value for each mask. The stroke participants' affected side was compared with the matched side of control participants. The NAPTI values were calculated for each trial and averaged over trials in standing and walking conditions, respectively. We used average pressure, rather than peak, as it shows the loading behavior of total mask area and time integral rather than peak values which reflect loading throughout stance.

The association between functional mobility and plantar pressure distribution were evaluated using a well-known and widely used measure of walking ability (the modified Walking Handicap Scale) to categorize stroke participants as either household or outdoor/ community walkers according where they were able to walk using a self-reported questionnaire. Criteria for each group have been developed according to the person's ability to conduct a series of critical functional ambulation tasks commonly performed in the home and community. The scale has been validated by expert clinicians but reliability is untested [18, 19].

SPSS (Statistical Package for the Social Sciences) for windows, version 16.0, was used to conduct statistical analyses. Independent t-tests was used to compare the data for the stroke and healthy control groups as data showed normal distribution checked with Shapiro–Wilk test ($P > 0.05$). Our predetermined alpha level of significance was set at 0.05 for all statistical procedures. To evaluate the contributions of the plantar pressure data to mobility, a binary logistic regression model was employed to select NAPTI values for the areas where pressure was most relevant and best contributed to the prediction of Mobility (a stepwise variable selection method). Mobility was selected as the dependent variable (i.e. household walkers=0, Community walkers=1) and plantar pressure variables (NAPTI variables that showed significant differences between the stroke and control groups ($P<0.05$)) were entered in as potential predictors.

Results

In comparison with control participants, stroke participants walked more slowly ($P<0.001$, 0.77 m

$s^{-1}\pm 0.26$ (95% CI 0.64–0.89) vs. 1.10 m s^{-1} ±0.14 (95% CI 1.03–1.17)), with a shorter stride length (P<0.001, 0.92m±0.25 (95% CI 0.80–1.03) vs. 1.24m±0.14 (95% CI 1.17–1.31)) and spent approximately 29% longer in double limb support phase (P=0.007, 0.25s±0.06 (95% CI 0.23–0.28) vs. 0.36s±0.12 (95% CI 0.30–0.42)).

Plantar Pressure Distribution while Standing

Table 1 shows the mean and standard deviation of NAPTI values of all segments while standing in the affected sides of the stroke group and the matched side of the control group. Compared to the control group, the stroke group showed greater pressure in lateral heel, less pressure in the medial and central forefoot and higher values in the lessor toes.

Plantar Pressure Distribution while Walking

Table 2 shows the mean and standard deviation of NAPTI values of all segments during stance phase of walking in the affected sides of the stroke group and the matched side of the control groups respectively. Compared with the control group, people with stroke showed 27% and 51% greater pressure on the lateral and medial heel respectively (P<0.05) and 25% and 20% less pressure on the medial and central forefoot respectively (P<0.05).

The Association between Plantar Pressure and Walking Ability

The stroke participants were categorized as household (45%, n=9) or community walkers (55%n=11). Household walkers walked more slowly (0.60±0.20 m.s-1 (95% CI 0.44–0.75) vs. 0.91±0.17 (95% CI 0.75–1.06) m.s^{-1}, p=0.005) than community walkers.

None of the standing plantar pressure variables (Table 1) made a significant contribution to the model (P>0.05). During walking, pressure on the medial heel was the only factor which differentiated between household and community walkers. The results of Wald statistics of the logistic regression models revealed that stroke participants with greater pressure on medial heel (odds ratio=1.11) were more likely to be household walkers (P<0.01). The coefficient of determination of models (Pseudo R-Square) indicated that the final regression models explained 29% of variance in mobility.

Discussion

Our findings show that stroke significantly affects plantar pressure distribution. The plantar pressure distribution differs significantly between the affected foot of people with stroke and healthy controls. During walking more pressure was borne through the heel area, especially the medial heel, and less through the medial and central forefoot. This is in keeping with previous work showing that people with stroke had a more everted rearfoot, slightly more inverted forefoot and a deficient heel and forefoot sagittal plane rocker function [5]. Increased pressure under the medial heel, which is assumed to indicate a more pronated foot, could be associated with plantarflexor stiffness and spasticity. If spasticity and stiffness limit ankle dorsiflexion but the heel remains on the ground, the necessary dorsiflexion is acquired by pronation of the subtalar joint which places more pressure on the medial heel [20]. less pressure through the medial and central forefoot is in accordance with weak push off which is a common clinical findings in the stroke population and usually attributed to plantarflexor weakness and the subsequent inability to overcome the inertia of the rest of the body [12, 21]. Spasticity may also prevent muscle lengthening and forward rotation of the tibia during stance phase, thereby hindering ankle dorsiflexion resulting in inefficient push-off. It is thought that plantarflexor spasticity during their lengthening

Table 1: The mean normalized average pressure-time integral values while standing (Affected versus Matched side)

Foot area	Matched side mean±standard deviation (SD)	Affected side mean±standard deviation (SD)	P value
Medial –HEEL	20.6±8.9	22.5±6.4	0.14
Lateral-HEEL	16.4±7.4	22.5±6.8	0.003
MIDFOOT	11.7±8.4	8.6±6.3	0.47
MP1 area	14.2±5.4	11.5±5.9	0.02
MP23 area	19.8±5.4	15.8±7.9	0.02
MP45 area	14.7±6.5	11.9±4.9	0.06
HALUX	1.0±1.5	3.2±3.4	0.07
LESSER-TOES	0.34±.63	1.8±1.7	0.009

Table 2: The mean normalized average pressure-time integral values during walking (Affected versus Matched side)

Foot area	Matched side mean±standard deviation (SD)	Affected side mean±standard deviation (SD)	P value
Medial HEEL	15.2±3.8	22.9±12.0	0.01
Lateral HEEL	13.9±2.8	17.7±6.6	0.02
MIDFOOT	9.3±6.4	8.1±5.4	0.51
MP1 area	17.0±3.9	12.7±6.1	0.01
MP23 area	19.8±5.2	15.9±6.4	0.04
MP45 area	12.8±3.3	13.6±5.5	0.58
HALUX	6.2±3.0	4.5±4.1	0.14
LESSER-TOES	2.9±1.6	2.2±1.9	0.22

period may perturb the lower limb kinematics and compromise the efficiency of push off [22].

However, these findings and our previous report of kinematic changes in the foot and ankle after stroke [5] contrast with the common clinical perception that the foot adopts a varus position after stroke [23-27]. This may have important clinical implications. For example, the standard choice of foot orthoses for stroke survivors is to use lateral wedges to correct the varus deformity [28] and improve balance or other gait parameters [29, 30]. There is however no evidence that this would address the increased heel loading and decreased forefoot loading in observed in this study. Furthermore, the medial heel pressures would likely be further elevated by a lateral wedge, if the effect of the wedge was to increase rearfoot eversion. Other strategies could be used to return plantar load distribution towards normal values, including footwear modifications, or alternative designs of foot orthoses, since both affect plantar pressure in predictable ways [31, 32].

Our results show that while standing, people with stroke bear more pressure on their lateral heel and lesser toes than healthy older controls. To some extent, this is in accordance with the results of static foot posture data on the same participants [5] which indicated that stroke participants had a slightly more supinated foot posture. Furthermore, flexing the lesser toes to apply greater pressure would be a function of the muscles that supinate the rearfoot. The results also concurs with the clinical description of claw toes in the hemiparetic foot [33]. Use of the heel and toes to bear more load would lead to reduced pressure under the mid and forefoot, which was also observed. Greater load under the toes might be a useful mechanism to control ankle moments and therefore postural sway, since the toes have the longest lever arm relative to the ankle. The lack of agreement between pressure data during standing and walking, and the lack of contribution from the standing pressure data to the walking ability model, illustrates the importance of assessing foot biomechanics after stroke under dynamic, rather than static conditions. This should not be surprising since the spasticity that characterizes neuromuscular dysfunction post stroke is sensitive to muscle lengthening velocity [34], which would differ in standing and walking tasks.

Our results have shown for the first time that plantar pressure distribution on the affected side during walking (but not standing) is a significant contributor to mobility post stroke. Stroke participants with greater pressure under the medial heel were more likely (1.11 times) to have limited mobility (i.e. be household walkers). These findings are consistent with the earlier observations that the foot is more pronated in stroke [5], and the common clinical belief that pronation of the foot is associated with walking disability or pathology. Further studies are required to investigate how changes in load distribution between the heel and forefoot (especially the medial heel), combine with other factors (such as altered kinematics [5]) to impair walking function. Thereafter appropriate interventions to target key aspects of foot function could be developed and tested in the belief that walking ability will subsequently improve.

Stroke participants walked significantly slower than control participants. The correlation between walking speed and lower limb biomechanics has been well documented [35-39]. Therefore, it is logical to assume that reduction in walking speed is a possible confounding factor associated with plantar pressure abnormalities found in our stroke study group. However, changes in plantar pressure patterns due to differences in walking speed did not show a speed-related offset of masked areas, as we observed pressure increased on the heel area and decreased on the forefoot area in the stroke group. To our knowledge, there are no reports of slower walking producing a shift in load from the forefoot to the heel which was observed in this study.

The main limitation of this study is, like most laboratory studies, the small number of participants recruited, the convenience of the sample, and large numbers of variables studied. In the absence of previous data to use for calculations, sample sizes were decided pragmatically based on the number of subjects that could be found in a limited time span. The level of significance was set at 0.05 to identify statistical differences and the clinical and functional significance of the differences found is unknown, thus the results are to be interpreted carefully given the known limitations.

Conclusion

The pattern of plantar pressure distribution in the stroke group was significantly different from the control group. Our results showed for the first time that plantar pressure distribution during walking is a significant contributor to limited mobility post stroke, but plantar pressure distribution during standing is not. These findings challenge prior assumptions about varus foot types in stroke and impacts of footwear and orthotic prescription for stroke survivors. Interventions that influence plantar pressure distribution, such as footwear and orthoses, could be used to address some of the biomechanical effects of stroke on the foot and walking

Conflict of interest: None declared.

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