Effects of Hallux Limitus on Plantar Foot Pressure and Foot Kinematics During Walking

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The effects of hallux limitus on plantar foot pressure and foot kinematics have received limited attention in the literature. Therefore, a study was conducted to assess the effects of limited first metatarsophalangeal joint mobility on plantar foot pressure. It was equally important to identify detection criteria based on plantar pressures and metatarsophalangeal joint kinematics, enabling differentiation between subjects affected by hallux limitus and people with normal hallux function. To further our understanding of the relation between midtarsal collapse and hallux limitus, kinematic variables relating to midtarsal pronation were also included in the study. Two populations of 19 subjects each, one with hallux limitus and the other free of functional abnormalities, were asked to walk at their preferred speed while plantar foot pressures were recorded along with three-dimensional foot kinematics. The presence of hallux limitus, structural or functional, caused peak plantar pressure under the hallux to build up significantly more and at a faster rate than under the first metatarsal head. Additional discriminators for hallux limitus were peak dorsiflexion of the first metatarsophalangeal joint, time to this peak value, peak pressure ratios of the first metatarsal head and the more lateral metatarsal heads, and time to maximal pressure under the fourth and fifth metatarsal heads. Finally, in approximately 20% of the subjects, with and without hallux limitus, midtarsal pronation occurred after heel lift, validating the claim that retrograde midtarsal pronation does occur. (J Am Podiatr Med Assoc 96(5): 428-436, 2006)

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cal restrictions and can be demonstrated with a simple static nonweightbearing measurement.

Dananberg argued that functional hallux limitus escapes detection in a static nonweightbearing situation. Moreover, because it is hidden from the naked eye, functional hallux limitus may be exposed only when sophisticated measuring techniques are used. Many people may exhibit normal dorsal mobility of the first metatarsophalangeal joint in a nonweightbearing situation but at the same time show restricted dorsiflexion when walking or running. This condition, however, is visible only on high-speed videotape or plantar-pressure recordings. This lack of evidence from qualitative clinical observation of hallux limitus explains why so many resulting clinical ailments remote from the foot, especially low-back problems, are unaccounted for and thus remain unresolved. In recent years, foot-pressure-measuring technology, in contrast with expensive high-speed videotape systems and associated biomechanical measuring software, has grown more popular among podiatric physicians. Therefore, there is a strong need for reliable detection criteria based on plantar foot pressure measurements.

This study had several goals. First, we sought to find existing relations between plantar-pressure variables and limited dorsiflexion of the hallux, measured statically in a nonweightbearing situation and dynamically during walking, representing structural and functional hallux limitus, respectively. The literature offers inclusion criteria for hallux limitus solely when measured in a static condition (Root et al and Buell et al). Second, it was equally important in this study to identify detection criteria based on plantar pressures and metatarsophalangeal joint kinematics, enabling differentiation between subjects functionally affected by hallux limitus and those with normal hallux function. In addition, we provide further information on the relation between midtarsal collapse and hallux limitus, kinematic variables relating to midtarsal pronation were also included in this study.

Methods

Test Population

Initially, 54 subjects were involved in this study. This number was reduced to 38 (age range, 20–55 years; weight range, 54–88 kg) to ensure that all of the subjects walked effortlessly and that the recorded data set was complete. To prevent left-right dominance from interfering with the walking pattern, only right-footed subjects were selected. Left-right dominance was determined by the foot preferred for kicking a ball. Written consent was obtained from all of the participants. Institutional review board approval was not necessary.

In a first analysis, this population was divided into two groups of 19 subjects each. The structural or static hallux limitus group was affected by limited static dorsiflexion of the first metatarsophalangeal joint of less than 70° in a nonweightbearing condition. The control group had superior or normal first metatarsophalangeal joint mobility and did not have a lower-limb dysfunction or chronic injury.

Dorsal mobility of the first metatarsophalangeal joint was measured with the subject nonweightbearing and lying prone. Using a classic goniometer with the legs aligned along the longitudinal axis of the hallux and the first metatarsal bone, first metatarsophalangeal joint range of dorsal motion was calculated as the angular difference between the position with the hallux aligned with the first metatarsal bone and the position at maximal dorsiflexion. The latter was measured with the hallux being dorsiflexed until firm resistance was sensed while the first metatarsal bone was fixed manually and the subtalar joint was left in a relaxed position. This measurement accords well with the definition of assisted hallux dorsiflexion as described by Buell et al. Because reference values for assisted dorsiflexion of the hallux are reported to range from 65° to 90°, it remains difficult to reach a consensus about what degree of limitation in first metatarsophalangeal joint dorsiflexion should be considered hallux limitus. In this study, the median value of 70° in the tested population was chosen as an acceptable hallux limitus separator, causing the hallux limitus group to score a mean ± SD of 54° ± 13° and the control group a mean ± SD of 85° ± 6° for hallux dorsiflexion mobility. These values compare well with the respective values of 55° and 82° for assisted hallux dorsiflexion reported by Buell and coworkers in their comprehensive study on first metatarsophalangeal joint static range of motion.

To concentrate on the more functional aspect of hallux limitus, as discussed by Dananberg, the same population as described previously was again divided into two subpopulations. One group represented people with a functional or dynamic hallux limitus, showing restricted dynamic dorsiflexion mobility of the first metatarsophalangeal joint during walking as observed from the three-dimensional (3-D) reconstruction. The remaining subjects with higher dynamic mobility acted as a control group. Here, the lower dorsiflexion limit was again set at the median value of 54°, which happens to be close to the population mean of 55°. This produced mean ± SD dynamic hallux dorsiflexion values of 47° ± 6° for the dynamic hal-
lux limitus group and 64° ± 7° for the control group. Note that both hallux limitus groups (static and dynamic) and, consequently, both control groups do not necessarily contain the same subjects, although the total populations are identical in the static and dynamic cases.

**Experimental Procedures**

All of the subjects were asked to walk at their preferred speed along a 22-m walkway with a built-in force plate in the middle (Kistler Instrumente, Zurich, Switzerland) covered with a pressure plate (Footscan; RSscan International, Olen, Belgium) to measure ground reaction forces and plantar foot pressures. The force plate was required only for the continuous dynamic calibration of the pressure plate using a so-called 3-D box calibration interface (RSscan). Approximately 4 m around this pressure plate, seven high-resolution and high-speed (250-Hz) infrared cameras (Vicon M1; Vicon, Oxford, England) were fixed at the ceiling. These cameras, connected to a Vicon 612 workstation (Vicon) for 3-D motion analysis, were used to record the foot kinematics. Each subject walked until at least five valid trials were recorded using the “midgait” protocol. To avoid targeting, the subject was asked to look straight ahead. A trial was accepted as valid when the force and pressure recordings were free of artifacts and visually closely resembled one another from trial to trial.

**Data Collection**

As for the foot kinematics, the following variables were measured: maximal dorsiflexion of the first metatarsophalangeal joint, time from first foot contact to maximal dorsiflexion of the first metatarsophalangeal joint (in percentage of stance duration), range of dorsiflexion of the first metatarsophalangeal joint, minimal navicular height, time to minimal navicular height (in percentage of stance duration), maximal navicular drop, time from the onset of midstance to first halluc contact with the ground, and time from maximal navicular drop to first halluc contact with the ground.

These measurements necessitated that five markers (14 mm in diameter) be affixed to specific areas of the foot: two on the medial halluc, two on the medial side of the first metatarsal bone (all lying in the same sagittal plane of the first metatarsophalangeal joint), and one on the medial navicular bone (Fig. 1). Because foot motion was recorded in 3-D, the kinematics were not affected by parallax errors. However, although there is little soft tissue beneath these markers, skin movements of the foot during walking may have affected the first metatarsophalangeal joint kinematics and, therefore, should be considered an inherent technical limitation of this study.

Plantar foot pressure was measured at the halluc, the five metatarsal heads, and the medial and lateral heel (Fig. 2). The pressure variables included peak pressure, time to peak pressure (in percentage of stance duration), loading rate, and time to maximal loading rate (in percentage of stance duration). Also, the ratios between peak pressure of the halluc and the first metatarsal head, between the first and second metatarsal heads, between the first and fifth metatarsal heads, and between the first + second metatarsal heads and the fourth + fifth metatarsal heads were calculated. The durations of the three main phases of stance—the heel-contact phase (from first heel contact to contact with the first or second metatarsal head), the mid-stance phase (from contact with the first or second metatarsal head to heel lift), and the propulsion phase (from heel lift to toe-off)—were also included.

**Statistical Tests**

For the statistical comparison between a hallux limitus population and its respective control group, a nonparametric Mann-Whitney test was selected to detect significant differences in the pressure and kinematic variables previously mentioned. The Mann-Whitney test was used because most data, according to a Kolmogorov-Smirnov test, proved to be nonnormally distributed. Furthermore, a nonparametric Spearman rank correlation was applied to the same data to reveal significant relations between static or dynamic metatarsophalangeal joint dorsal mobility and the...
pressure and kinematic variables previously described. All significance levels were set at $P < .05$. All of the statistical tests originated from the well-known SPSS software program (SPSS Inc, Chicago, Illinois).

**Results**

In the statistical comparison between the static hallux limitus group and the control group, the following variables were different for the left and right feet: dynamic range of dorsiflexion of the first metatarsophalangeal joint during walking ($P = .008$ and .014 for the left and right feet, respectively), the ratio between peak pressure of the hallux and the first metatarsal head ($P = .023$ on the left and $P = .049$ on the right), and the loading rate of the hallux ($P = .043$ on the left and $P = .040$ on the right) (Fig. 3). The latter implies that the resistance due to a limited first metatarsophalangeal joint affected by hallux limitus caused not only much higher pressure loads under the hallux than under the first metatarsal head but also steeper loading curves of the hallux (Fig. 2B). It also reduced the amount of dynamic hallux dorsiflexion during walking (Fig. 4).

There were also secondary differences found only in the left or right foot alone. The left foot revealed reduced peak dorsiflexion for the dynamic first metatarsophalangeal joint ($P = .049$) and earlier peaking of first metatarsophalangeal joint dorsiflexion ($P = .003$) (Fig. 5). As for the right foot only, the ratios of peak pressure between the first and second metatarsal heads, the first and fifth metatarsal heads, and the first + second metatarsal heads and the fourth + fifth metatarsal heads showed an unloading of the first metatarsal relative to the more lateral forefoot ($P = .009$–.039) (Fig. 6).

Besides looking for differences between people affected and not affected by hallux limitus, it was also interesting to observe how static dorsal mobility of the first metatarsophalangeal joint correlated with the other measurement variables, especially with dynamic dorsiflexion range of the first metatarsophalangeal joint. The Spearman rank correlation factors for the latter were 0.45 for the left and 0.36 for the right foot. Other correlation factors relating static dorsal mobility of the first metatarsophalangeal joint with pressure variables and being significantly different for the left and right feet proved to be low, ranging from 0.34 to 0.39.

Similarly, the dynamic hallux limitus group, demonstrating reduced dynamic or functional mobility of the first metatarsophalangeal joint during walking, was now compared statistically with its respective control group. For both feet, the static dorsiflexion range of the first metatarsophalangeal joint was also significantly lower for the affected group ($P = .005$ and .034 in the left and right feet, respectively) (Fig. 7). This was expected because static and dynamic first metatarsophalangeal joint mobility were previously shown to correlate rather well. The former observation was also true for the peak dynamic first metatarsophalangeal joint dorsiflexion ($P = .001$ for both feet), with correlation factors as high as 0.59 and 0.68 for the left and right feet, respectively.

Further assessment of the left foot revealed for dynamic hallux limitus an enhanced ratio between the peak pressure of the hallux and the first metatarsal head ($P = .041$), similar to the static hallux limitus
group (Fig. 8). In addition, the peak pressure of the first metatarsal head and, as with the left hallux limitus feet, the time of peaking for dynamic dorsiflexion of the first metatarsophalangeal joint scored significantly lower in the presence of functional hallux limitus \( (P = .049 \text{ and } .008, \text{ respectively})\). The right foot only shows the pressure under the fourth and fifth metatarsal heads to peak significantly later than in the control group \( (P = .030 \text{ and } .028, \text{ respectively})\) (Fig. 9).

**Discussion**

This study investigated the effects of static (structural) and dynamic (functional) hallux limitus on plantar pressure and first metatarsophalangeal joint dorsal

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**Figure 3.** A, Mean static and dynamic range of first metatarsophalangeal joint dorsiflexion for the static hallux limitus (HL) and control groups. B, Mean ratio of peak pressure between the hallux and the first metatarsal head (M1) (first two sets of bars) and mean loading rate of the hallux for the static HL and control groups (second two sets of bars). Error bars represent SE.

**Figure 4.** Typical time history of dynamic dorsiflexion of the first metatarsophalangeal joint (MTPJ) and navicular drop during walking for hallux limitus (HL) (A) and non-HL (B) subjects. The first vertical line defines the time of forefoot contact (with either the first or second metatarsal head), and the second vertical line indicates the time of heel lift.
mobility. As expected, the static and dynamic measurements correlated significantly with each other, with correlation factors of 0.45 and 0.36 for the left and right feet, respectively. Because the lack of static dorsal mobility of the hallux is assumed to also impair dynamic mobility during walking, one would have expected this correlation factor to be much higher. Observing the individual scores for static and dynamic range of hallux dorsiflexion reveals that only 68% of the left and 50% of the right feet affected by static hallux limitus also show dynamic or functional limitation of hallux dorsiflexion. This suggests that a static or structural limitation of hallux dorsiflexion does not necessarily cause functional first metatarsophalangeal joint dysfunction and that it is not inevitable that it will impair first metatarsophalangeal

![Figure 5](https://example.com/figure5.png)

**Figure 5.** Mean maximal dynamic dorsiflexion of the first metatarsophalangeal joint (MTPJ) (first set of bars) and the time from first heel contact to maximal first MTPJ dorsiflexion (second set of bars) for the left foot of the static hallux limitus (HL) and control groups. Error bars represent SE.

![Figure 6](https://example.com/figure6.png)

**Figure 6.** Mean ratio of peak pressure between the first (M1) and second (M2) metatarsal heads, first and fifth (M5) metatarsal heads, and first + second and fourth (M4) + fifth metatarsal heads for the right foot of the static hallux limitus (HL) and control groups. Error bars represent SE.

![Figure 7](https://example.com/figure7.png)

**Figure 7.** Mean dynamic and static range of the first metatarsophalangeal joint (MTPJ) dorsiflexion and maximal dynamic first MTPJ dorsiflexion for the dynamic hallux limitus (HL) and control groups. Error bars represent SE.
joint motion. One reason for this phenomenon may be that a structural limitation, if not too rigid, may be overcome by the large ground reaction forces acting on the forefoot and hallux during propulsion, especially during gait in young adults, who formed the main part of this test population. However, although motion in the first metatarsophalangeal joint may look normal in this way, resistance to hallux dorsiflexion and the resulting strain may increase and thus contribute to overload.

Of all kinematic variables measured, the dorsiflexion range of the first metatarsophalangeal joint is the only strong discriminating variable for the detection of static hallux limitus (Fig. 3A), although reduced peak dorsiflexion of the first metatarsophalangeal joint and its early peaking during walking may also suggest the presence of not only static (Fig. 5) but also functional (Figs. 7 and 8) hallux limitus. Measuring plantar pressure, on the other hand, seems to offer more powerful discriminating tools to detect hallux limitus.

The most important pressure measurements were the ratio between the peak pressure of the hallux and the first metatarsal head and the loading rate of the hallux (Fig. 3B). This is understandable because during heel lift, a stiff first metatarsophalangeal joint will cause the first metatarsal head to unload, thereby shifting all of the load toward the distal hallux in the same way that the weight of a bridge is redistributed to its supporting pillars. On the color plantar foot pictures representing peak pressure during the stance phase available on even the simplest of foot-pressure systems, it is easy to qualitatively screen differences in peak pressure between the hallux and the first metatarsal head (Fig. 2A). This variable is, therefore, a powerful discriminator for clinical use. With the increasing popularity of foot-pressure–measurement devices in podiatric medical practices, this variable may be very useful in diagnosing the functional limitations caused by static or structural restrictions of the first metatarsal in walking and running. On more sophisticated pressure devices that also provide information about the loading rate of the pressures measured, the presence of high loading rates offers additional evidence of the eventual occurrence of a dynamic or functional dorsiflexion limitation of the first metatarsophalangeal joint.

Other interesting significant indicators of hallux limitus, although in this study found only for the right foot, were all variables referring to the dominance of lateral over medial forefoot pressure, such as the ratios between the first and second metatarsal heads, the first and fifth metatarsal heads, and the first + second and fourth + fifth metatarsal heads (Fig. 6). All of these pressure results are in accordance with the study by Bryant et al,8 claiming higher loads under the hal-
lux and lateral metatarsal heads in the presence of limited, statically assessed hallux dorsiflexion. These results seem to be a logical consequence of the unloading of the first metatarsal head due to the presence of hallux limitus. Also, for the right foot only, functional hallux limitus seemed to delay pressure peaking of the lateral forefoot (the fourth and fifth metatarsal heads) during propulsion (Fig. 9). This could be explained by an avoidance strategy to bypass medial obstruction, thereby shifting to a more lateral roll-off path of the foot before final lift-off.

Finally, as seen in Figures 3 to 9, more significant differences are found in the hallux limitus group selected on the basis of static (structural) rather than dynamic (functional) hallux limitus measurement of first metatarsophalangeal joint mobility. A logical explanation may be that dynamic measurements from videotape recordings are much more affected by statistical noise (variance), making small differences more difficult to detect than with static measurements using a simple goniometer. In light of the present debate on whether midtarsal joint pronation occurs as a result of limited motion of the first metatarsophalangeal joint or actually causes the first metatarsophalangeal joint to lock, one of the implicit aims of this study was to acquire information about the timing of peak midtarsal pronation, as represented by maximal navicular drop relative to peak first metatarsophalangeal joint dorsiflexion.

Some podiatric physicians claim that midtarsal pronation and eventual midfoot collapse occur in part as a retrograde phenomenon and as a result of hallux limitus. The alternative theory proposes that midtarsal pronation due to rearfoot pronation is one of the causal factors leading to functional hallux limitus. In this study, approximately 20% of the subjects demonstrated maximum navicular drop after heel lift had begun. The number of retrograde cases may grow to 30% by correcting for the heel delay observed with hallux limitus feet, suggesting that more than one-fifth of the subjects demonstrated a type of retrograde pronation distinct from rearfoot, impact-related pronation. Although navicular drop is considered a good estimator of midtarsal pronation, it is not certain whether maximum navicular drop is the best method by which to study the timing of pronation because midtarsal stiffness and general range of motion were not assessed in this study. What was determined, however, is that a significant sample of the population analyzed in this study demonstrated retrograde pronation, and this seems to validate the claim that this phenomenon does occur. However, not all of the subjects demonstrating this retrograde pronation are affected by hallux limitus, functional or structural. It can, therefore, be assumed that the retrograde response may be due to additional factors in the foot structures. Further examination is required to obtain a more definitive analysis of these data.

One limitation of this study is that the population studied was rather young. According to Buell et al, lack of dorsal mobility of the first metatarsophalangeal joint increases with age. Although the age of the subjects in the present study ranged from 20 to 55 years, the mean ± SD age was only 24 ± 10 years, implying that the present results reflect the hallux limitus behavior of mainly young adults. This finding may have affected the low correlations between static and dynamic hallux limitus and may offer an additional reason why structural hallux limitus, as measured by a lack of static hallux dorsiflexion, does not always result in an equivalent lack of dynamic mobility during walking.

A second limitation of this study is that dynamic (functional) hallux limitus was analyzed during walking only. Knowing that the relative duration of the propulsion phase is much longer during running than during walking, implying that a lack of hallux dorsiflexion may be more harmful when moving at higher speeds, repeating the same experiments for running would be of great interest, especially for clinicians who treat joggers and runners.

A final limitation is that until now there has been no generally accepted standard for measuring dynamic hallux dorsiflexion. Different marker placement may affect hallux kinematics during locomotion, or an alternative choice of the neutral hallux position may alter the values of the dorsiflexion data.

**Conclusion**

The presence of hallux limitus, structural or functional, causes plantar pressure to build up under the hallux significantly more than under the first metatarsal head. Also, the loading rate of the hallux is significantly increased. Additional discriminators for hallux limitus may be peak dorsiflexion of the first metatarsophalangeal joint and the time to this peak value, the pressure ratios of the first metatarsal and the more lateral metatarsal heads, and the time to maximal pressure under the fourth and fifth metatarsal heads. Furthermore, the occurrence of structural hallux limitus does not necessarily imply that functional hallux limitus is also present. Finally, there is no clear causal relation between midtarsal pronation and hallux limitus. Most people, whether or not affected by hallux limitus, demonstrate midtarsal pronation, if present, before heel lift and thus hallux dorsiflexion. However,
more research is needed to reveal the biomechanical nature of this phenomenon.

References