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Original Research

Gait and Balance Biomechanical Characteristics of Patients With Grades III and IV Hallux Rigidus

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A R T I C L E I N F O

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A B S T R A C T

Patients with hallux rigidus (HR) tend to develop a characteristic alteration in walking to lessening pain and compensate for the limited range of motion at the first metatarsophalangeal (MTP1) joint that might be affected balance and gait. The goal of this study was to perform an integrated biomechanical description of gait and balance of symptomatic patients with either grade as III or IV HR in comparison with healthy subjects. Eleven patients (7 men) with HR (60 ± 7 years, 1.60 ± 0.07 m, and 70 ± 13 kg) and 16 (7 men) healthy subjects (70 ± 8 years, 1.66 ± 0.10 m, and 74 ± 14 kg) were included. Subjects performed 2 tasks: walking (5 trials of straight walking for at least 6 meters) and bipedal quiet standing for 30 seconds. For these 2 tasks the following variables were measured: range of motion of the MTP1 joint, plantar pressure distribution during the stance phase of walking, and the postural sway during quiet standing. Plantar pressure was measured in up 15 walking trials with a mat pressure sensor. The MTP1 joint range of motion for flexion/extension during walking was significantly smaller for the patients with HR than for the control group (HR: 14 ± 8°, control: 44 ± 5°; $t(17) = -9.7$, $p < .001$). The forefoot plantar pressure distribution among different regions of the foot in patients with HR was not statistically different than the control group, but there was a tendency of higher pressures in the lateral metatarsal heads ($p = .06$). As description of the postural sway during quiet standing, the center of pressure area was not different between HR and the control group ($p > .05$). Decreased MTP1 joint range of motion for flexion/extension during walking in symptomatic high-grade HR patients can be associated with higher pressure in the lateral metatarsal heads while the impact on postural sway is not affected.

The term hallux rigidus (HR) describes a condition characterized by pain, stiffness, swelling and reduction in the range of motion, especially dorsiflexion, at the first MTP joint (1). The severity of HR is usually evaluated by a scale based on clinical and radiographic signs, ranging from I to IV (2). Patients with grades III and IV HR usually present dorsiflexion ≤ 10° and/or 75% to 100% loss compared with normal side. There is notable loss of metatarsophalangeal plantar flexion as well, often ≤ 10° of plantar flexion (2). In addition, they have substantial articular space narrowing, possibly periarticular cystic changes, more than ¼ of dorsal joint space involved on lateral radiograph, sesamoids enlarged and/or cystic and/or irregular and clinical signs of constant pain and substantial stiffness at extremes of range of motion but not at mid-range for grade III and pain at mid-range of passive motion for grade IV (3).

Patients with HR tend to develop a characteristic alteration in walking to lessening pain and compensate for the limited range of motion at the first MTP joint (2,4). They may shift their weight to the lateral side of the foot, thus increasing loads under the lateral metatarsal heads (5-8), and "toeing off" over the lesser metatarsal (fourth and fifth) heads (5,8). Indeed, it has been observed increased loading under the lesser toes and hallux (8-13), reduced loading under the first MTP joint (14), and reduced hallux dorsiflexion throughout stance and swing phases during walking (15). However, most of these studies have investigated patients with grades I and II HR. Patients with grades III and IV HR might present particular changes in locomotion.

Besides locomotion, another important task that might be affected by the HR disorder is the maintenance of balance. The control of posture is a complex task performed by the central nervous system and it is achieved by the integration of different types of sensory information and by the passive and active properties of the musculoskeletal system (16). During standing, the feet are the link between floor and the rest of the body and any disorder in the feet might deteriorate the correct sense and force transmission necessary to maintain balance. It has been

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reported that foot pain impairs balance in elderly people (17). However, we are not aware of any reported research that has investigated posture control in patients with HR disorder in force plate. Such an investigation can be done with the assessment of the postural sway during standing and could contribute for the understanding of potential impairment to the patients' quality of life.

Therefore, the goal of this study was to perform an integrated biomechanical description of the gait and balance of grade III and IV HR patients in comparison with healthy subjects. We hypothesize that in comparison with control subjects, the HR grades III and IV patients would present: (1) increased plantar pressure on the lateral metatarsal heads, lesser toes and hallux along with decreased pressure on the first MTP joint during walking; and (2) increased postural sway during quiet standing.

Patients and Methods

This study was approved by a local ethics committee and informed consent was obtained from each participant. The inclusion criteria for the HR group were: symptomatic presentation of HR; grades III or IV; indication for either MTP joint arthroplasty or arthrodesis. All the HR patients underwent surgery after the study. The exclusion criteria for the control group were: any previous surgery in the foot/ ankle; any symptoms or complains in the foot/ ankle/ knee at the time of enrollment.

Eleven patients (7 men: 4 women) with HR volunteered to participate in this study (mean $\pm$ 1SD age 60 $\pm$ 7 years, height 1.60 $\pm$ 0.07 m, and body weight 70 $\pm$ 13 kg). Additionally, 16 healthy subjects (9 women: 7 men) volunteered for the control group (mean $\pm$ SD age 70 $\pm$ 8 years, height 1.66 $\pm$ 0.10 m, and body weight 74 $\pm$ 14 kg). None of these anthropometric variables were significantly different between groups. The HR patients have been clinically and radiographically classified with degrees III or IV in the scale proposed by Coughlin and Shurnas (18).

All the subjects were requested to perform 2 tasks: walking and quiet standing (Fig. 1). For these 2 tasks the following variables were measured: range of motion of the first MTP joint, plantar pressure distribution during the stance phase of walking, and the postural sway during quiet standing.

Regarding the walking task, each subject performed at least 5 trials of walking straight for at least 6 meters. The foot kinematics during walking of each participant was registered with a 3-dimensional motion analysis system (Vicon 460, Oxford Metrics, Oxford, UK) operating at 120 Hz, and the stance phase of the gait was determined using the vertical ground reaction force measured by a force plate (OR6-2000, AMTI Inc., Watertown, USA) embedded in the floor and operating at 1080 Hz. To measure the flexion/ extension angle of the first MTP joint, 3 small reflective spherical markers were placed on the subject's first ray using these anatomical references: (1) proximal region of the first metatarsal bone, (2) first MTP joint center of motion, and on the tip of the great toe (Fig. 2).

The flexion/extension MTP joint angle was defined as the sagittal plane angle formed by the 2 lines that connect the 3 markers already mentioned and it was calculated using the Visual3D software (C-Motion Inc., USA). The MTP joint angle data were low-pass filtered at 6 Hz with a sixth-order Butterworth filter and zero phase lag. The range of motion was computed as the maximum minus the minimum angles during the stance phase. The subjects were requested to walk again in order to measure the plantar pressure with a mat pressure sensor (Tekscan F-Scan Mobile System, USA) placed on the walkway floor. The subjects performed up to fifteen trials to measure the pressure distribution. Using the appropriate software for this pressure mat, we calculated the mean plantar pressure across ten trials and from this mean data, the plantar peak pressure on the following regions: hallux (H), first metatarsal head (MT1), second metatarsal head (MT2), third, fourth and fifth metatarsal head (MT345). We then normalized these values dividing the value of each region by the sum of plantar pressures in all forefoot regions.

Regarding the standing task, each subject was asked to stand as quietly as possible for 30 seconds and with their feet separated at shoulder width on the force plate. We manipulated the visual information by requesting the subjects to stand with the eyes open or closed in different trials. The rationale is that the elimination of the visual information challenges the posture control system and accentuates the need for other sensorial information, increasing a possible related-effect to the HR disease if there is one. All the subjects performed 3 trials in each visual condition, which were alternated, and at the eyes-open condition the subjects were instructed to look straight at a point about 3 meters ahead at his or her head height. We recorded the forces and moments measured by the force plate at a sampling frequency of 100 Hz and we analyzed the center of pressure (COP) displacement in the anterior-posterior and medial-lateral directions. The COP data were low-pass filtered at 10 Hz with a fourth-order Butterworth filter and zero phase lag. To describe the postural sway, we computed the area and mean velocity of the COP displacement. The COP area was estimated by fitting an ellipse to the COP data (in the anterior-posterior versus medial-lateral plane) that encompasses 95% of the data. The COP mean velocity was calculated as the total COP displacement in the plane divided by the total period (19).

Normality of the data was verified using the Lilliefors' test and only the postural sway variables did not present normal distribution. In this case, the data were normalized using a natural logarithm transformation and the descriptive data, mean and confidence interval, were calculated at the natural-logarithm space and transformed back using the exponential function. Independent 2-tailed *t* tests were employed to determine the difference between groups for the investigated variables. The homogeneity of variances between groups was verified using an F-test of equality of variances and if the variances of the 2 groups were different, the Satterthwaite's approximation for the effective degrees of freedom was employed in the t-test. This procedure was necessary only for the peak plantar pressure variables. A significance level of 0.05 was employed in all statistical tests, which were performed using the Matlab software (Mathworks Inc., Natick, USA). Due to data collection problems, data for some subjects in different analyzes were disregarded, the

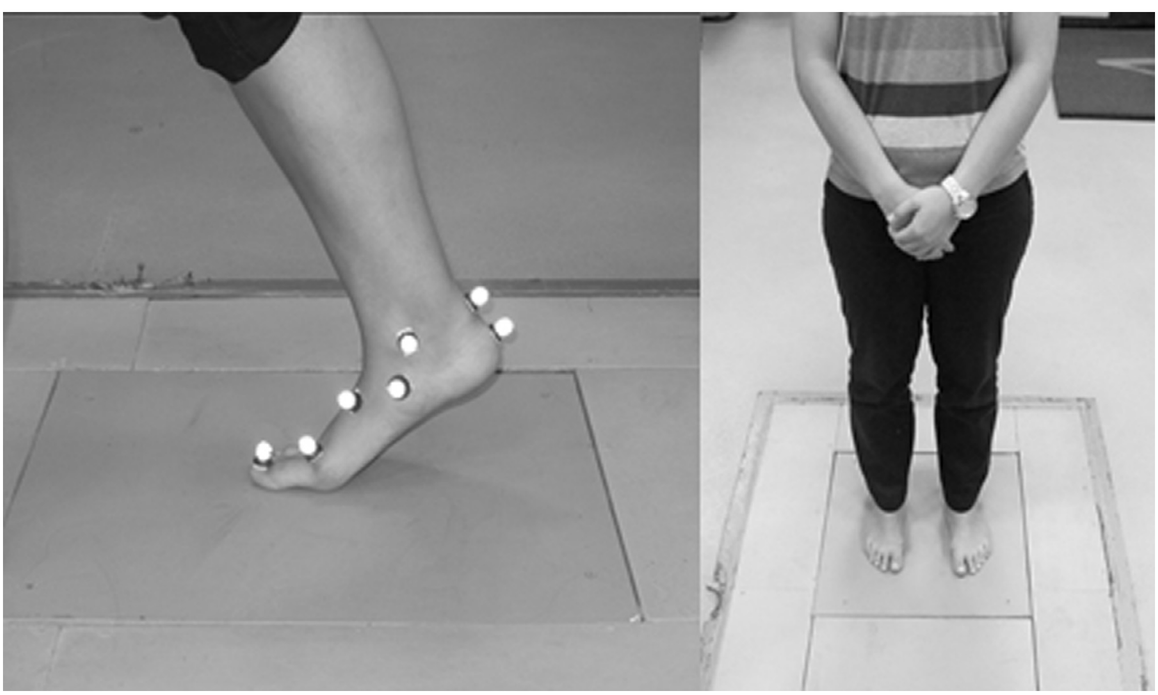

Fig. 1. Walking and quiet standing tasks.

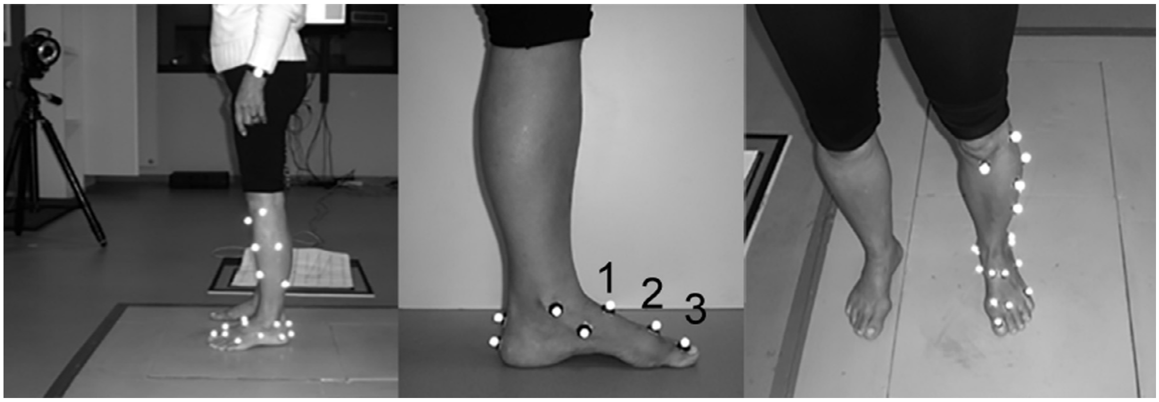

Fig. 2. Positioning of the reflective spherical markers' placement and definition of the flexion/extension MTP1 joint angle: (*A*) proximal region of the first metatarsal bone, (*B*) MTP1 joint center of motion, and (*C*) on the tip of the great toe.

actual number of subjects investigated in each analysis is presented with the results in the next section.

Results

First MTP Joint Range of Motion (ROM) During Walking

The average temporal patterns of the flexion/extension angle of the first MTP joint during the stance phase of walking for the patients with HR and control group are shown in Fig. 3. The first MTP joint range of motion for flexion/extension during walking was significantly smaller for the patients with HR than for the control group (HR: 14 ± 8°, control: 44 ± 5°; t(17) = -9.7, $p < .001$).

Plantar Pressure Distribution During Walking

The plantar pressure distributions among different regions of the foot in HR patients were not statistically different ($p > .05$) than that found in the control group (Table 1).

Postural Sway During Quiet Standing

There was no statistical difference between the patients with HR and the control group regarding their postural sway; the variables COP area and COP mean velocity were not different ($p > .05$) for the conditions with eyes open and closed during bipedal quiet standing (Table 2).

Table 1
Mean ± SD of the forefoot plantar pressure distribution at different forefoot regions and comparison between hallux rigidus (N = 10) and control (N = 16) groups

Region	Hallux Rigidus	Control	*p* Value
MT1 (%)	11.8 ± 2.8	14.6 ± 4.9	.10
MT2 (%)	16.3 ± 3.6	18.9 ± 4.4	.14
MT345 (%)	54.8 ± 8.3	49.5 ± 5.7	.06
H (%)	17.1 ± 10.0	17.0 ± 5.4	.98

Abbreviations: MT1, first metatarsal head; MT2, second metatarsal head; MT345, lateral metatarsal heads; H, hallux.

Table 2
Mean and 95% confidence interval of the postural sway variables and comparison of the postural sway during quiet standing between the hallux rigidus (N = 11) and control (N = 13) groups

COP Variable	Hallux Rigidus	Control	*p* Value
AO [cm^2]	0.98 (0.70, 1.37)	0.93 (0.70, 1.24)	.80
AC [cm^2]	1.23 (0.86, 1.78)	1.23 (0.74, 2.05)	.99
VO [cm/s]	0.95 (0.52, 1.76)	1.18 (0.91, 1.53)	.47
VC [cm/s]	1.10 (0.58, 1.96)	1.40 (0.92, 2.13)	.42

Center of pressure (COP) area (A) and COP mean velocity (V) at the open (O) and closed (C) eyes conditions.

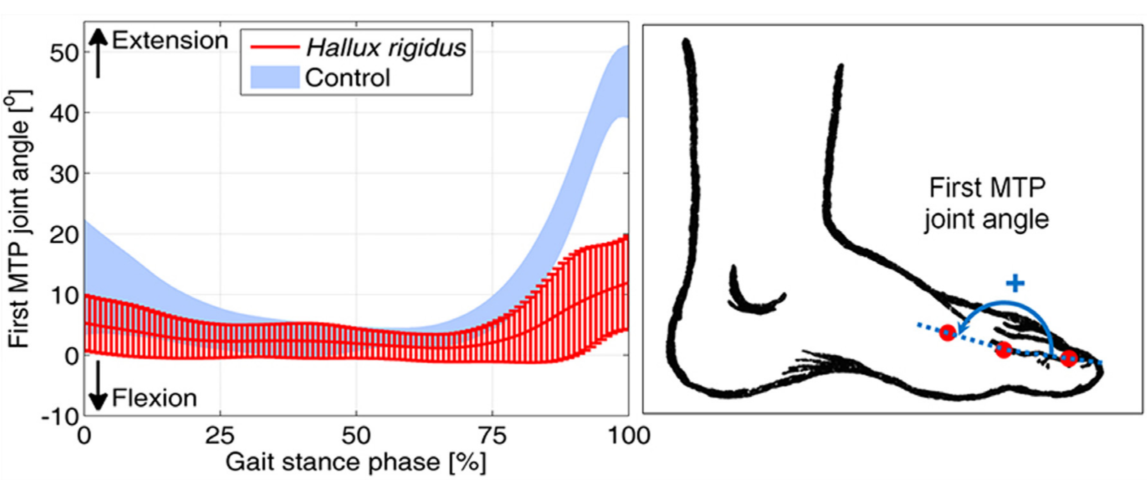

Fig. 3. Left side: Mean ± SD patterns of the flexion/extension angle of the MTP1 joint during walking for patients with HR and control group; Right side: positioning of the reflective markers' placement and definition of the flexion/extension MTP1 joint angle.

Discussion

To understand the impact of the symptomatic grades III and IV HR on the normal gait and balance we investigated the flexion/extension range of motion of the first MTP joint, the plantar pressure during walking, and the postural sway during quiet standing of these patients in comparison with healthy subjects. It worth to mention that the patients included in the HR group were all evaluated at the preoperative stage (arthroplasty or arthrodesis) and represent a severe HR presentation. We hypothesized that all these variables would be affected in the patients with HR but this hypothesis was only partially confirmed.

Our results showed that the first MTP joint range of motion for flexion/extension during the stance phase of walking was significantly smaller for the patients with HR in comparison with the control group. During the stance phase of walking the predominant movement of the first MT is dorsiflexion, and this movement was observed for the 2 groups. The average range of motion of the great toe during walking for the control group ($44 \pm 5°$) was in agreement with previous studies (8,15); the average maximum dorsiflexion of the HR patients was 14° in this study, less than the 19° or 28° reported by other authors (8,20). This difference may be attributed to the disparity of the HR grades included in different studies. In severe HR cases (grades III and IV HR), as in our study, the hallux motion is severely compromised, resulting in frequent pain and significant limitation of motion (18).

The plantar pressure in HR patients has been previously discussed in the literature and the majority of the studies demonstrated increase loading under the lesser toes and hallux (3,10-12,14). According to Bojson-Moller (21) and Bryant (11), this result can be explained using the concept of high- and low-gear push off. This model suggests that in the presence of restricted first MPJ motion, propulsion occurs through the oblique axis (axis connecting the second to fifth metatarsal heads), which subjects the lateral forefoot and toes to increased loading and results in hyperextension of the interphalangeal joint of the hallux prior to toe-off (14). Our results demonstrated that there are no statistical differences between the peak plantar pressure values at forefoot regions during walking for the HR patients and for the normal control group. However, in this study, we observed a tendency of higher peak plantar pressures at MT345 regions for the patients with high-grade HR ($p = .06$). This result may be attributed to the lateral deviation of COP. It is likely that in the presence of painful first MPJ OA, people with HR consciously adjust their gait pattern to avoid overloading the painful area. This antalgic gait pattern may lead to increased loading of the lateral metatarsal heads (14). Furthermore, our results have not shown the increased loading under the lesser toes and hallux as shown in previous studies (8-12). This is likely due to the higher age range of our sample, which presents gait adaptations as a consequence of decreased in muscles strength, more energy cost during gait, soft tissue and joint stiffness decreased of joint's range of motion, decreased gait velocity and step length. Therefore, due to natural age adaptations, our sample have shown lower capacity of antalgic gait. However, because previous studies (5,8) have been observed increased loading under the lateral metatarsal heads for the HR patients, it's possible that our result may be attributed to the small sample size which is one limitation of this study.

We evaluated the balance performance of the subjects during a standing task where the subjects had to stand as still as possible for 30 seconds. This is a standard evaluation method in the field. We observed that the postural sway of the HR patients in comparison with the control group, measured by the variables area and mean velocity of the center of pressure displacement, were not different for the eyes open and closed conditions during standing. No studies were found about the postural sway of the HR patients specifically. Possibly, only the motion restriction at the first MTP itself is not enough perturbation to change the postural sway during quiet standing, even with closed eyes. Perhaps the postural sway of the HR patients could change if the task of the study were more dynamic and challenging.

The results of this study need to be interpreted in the context of the its specificity and its limitations. The relatively small sample could underestimate differences between groups and additional studies would be beneficial. On the other hand, this study evaluated a very specific population, symptomatic elderly patients with severe degrees of HR, neither involving young individuals nor with initial degrees of osteoarthrosis. We encourage other research groups to complement our findings on this subpopulation.

In conclusion, severe HR (grades III and IV HR), is associated with lower MTP joint range of motion than healthy subjects for flexion/extension during walking, and also lower than the values reported in the literature for grades II and II HR. However, despite this severe limitation, relative plantar pressure at the forefoot regions during walking and the postural sway during standing were not altered by HR when compared with a control group.

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