ORIGINAL ARTICLE

Ground reaction force patterns during gait in patients with lower limb lymphedema

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ABSTRACT

Although gait problems have been reported in patients with lower limb lymphedema (LLL), the gait pattern (GP) changes have not been documented yet. However, it is possible that patients with LLL show abnormal GP that can be related to biomechanical complications related to osteoarthritis or falls affecting the quality of life. Ground reaction force analysis during gait allows objective assessment of the patients and it can be used to plan a rehabilitation approach. **Objective:** To analyze the GRF during gait in patients LLL. **Methods:** An experimental descriptive study was realized with twenty-three LLL patients, both unilateral and bilateral and classified as moderate and severe, participated in the experiments. The patients walked on a force plate while the three ground reaction force (GRF) components, vertical, mediolateral (M-L) and anteroposterior (A-P), under their feet were recorded and analyzed. **Results:** In the patients with unilateral lymphedema, either moderate or severe, the vertical GRF components of the affected limb were similar to the sound one and also resembling those found in healthy adults. The M-L GRF was smaller in the non-affected side. In patients with bilateral lymphedema gait speed was significantly slower. More interestingly, the vertical GRF pattern was flat, not showing the typical 2-peak shape. Finally, the large M-L forces found suggest gait stability problems. **Conclusions:** The patients showed abnormal GRF patterns, including compensation with the non-affected leg. The GRF variability was higher in the patients with severe unilateral lymphedema. Bilateral lymphedema results in lower A-P forces. Stance phase duration was longer in patients with bilateral and severe lymphedema.

Keywords: Lymphedema, Gait, Lower Extremity, Obesity

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INTRODUCTION

Lymphedema is the swelling of a body part, usually arms or legs, due to the accumulation of lymph fluid. This is a chronic and progressive condition that requires specific management for a lifetime and has several complications from a biomechanical point of view that has not been receiving much attention in the literature. The gait pattern (GP) of patients with lower limb lymphedema (LLL) has been barely studied despite a common consensus in the medical community with respect to the presence of abnormal motion in these patients. Biped locomotion is a characteristic way human gait that can be regarded as a quasi-cyclical movement with sequential alternative stance and swing of one foot or both[1,2] in order to displace the body while maintaining upright balance. It is possible to measure the ground reaction forces (GRF) during gait that are related to the acceleration of the total body center of mass.[3] The force platforms measure the three-dimensional GRF components: anteroposterior (A-P), mediolateral (M-L) and vertical. Other devices, such as plantar pressure insoles, only record the vertical GRF component, although with optimization methods they can be used to estimate the complete GRF.[4]

Several chronic and disabling complications of LLL have been reported in the medical literature.[5,6] However, up to date, none has focused on the lymphedema complications from a biomechanical point of view. In the literature, the orthopedic problems related to lymphedema have been barely addressed. A poor mobility may worsen the edema which, in turn, impairs the range of motion of the joints. Therefore, it is possible that edema of the legs restricts the motion of hip, knee and ankle joints, thus affecting the GP. A proper understanding of the orthopedic findings should therefore be considered in the diagnosis and treatment of lymphedema.[7] Gait can be affected by lymphedema and an adequate gait function has been reported as the best determining factor of quality of life.[8]

Although gait problems have been reported in patients with LLL, the analysis of their GP has been based on qualitative assessments.[9,10] A preliminary study with a small number of patients pointed out that patients with lower limb lymphedema showed abnormal GRF[11] that might cause biomechanical complications and these may affect self-dependence and quality of life. The GP analysis is an important tool to assess and follow-up patients and it is very useful to plan therapeutic and rehabilitation programs. However, up to date, there is no study of the gait biomechanics of lymphedema patients.

If we consider that the increase in mass in lymphedematous limb(s) could be similar from a biomechanical point of view, to a type of overweight/obesity, it can be expected that LLL patients also show similar GP to those previously documented in overweight/obese population.[12-16] Their walking speed is slower[2,3], their stride length is shortened,[15,16] and their step width is wider.[17-18] They adapt the GP to minimize the consequences of the higher vertical and propulsive ground reaction forces (GRF) in the musculoskeletal system. Moreover, they have problems to maintain mediolateral balance as indicated by the M-L GRF.[19]

The biomechanical analysis of gait in lymphedema patients has, to our knowledge, not been published yet. It can be hypothesized that the leg mass increased by lymphedema has several implications on the biomechanics of gait with altered GRF patterns, and these effects may be dependent on the severity of the lymphedema and its side, whether unilateral or bilateral.

In the case of unilateral lymphedema, it can be hypothesized that the mass increase of the affected leg may cause gait asymmetry. This asymmetry would affect the step length as well as the GRF patterns with differences in the M-L forces of both legs. Regarding the bilateral lymphedema, it is expected that gait would be similar to the gait of obese people, as they share some common aspects related to overweight of both legs.

OBJECTIVE

The objective of this study was to analyze the ground reaction forces (GRF) during gait in patients with lower limb lymphedema (LLL).

METHODS

An observational study was conducted to assess gait abnormalities in patients with LLL.

The study procedures were conducted in accordance with the ethical guidelines of the local hospital and with the Helsinki Declaration. All the patients voluntarily participated in the study and signed an informed consent form agreeing that their data could be used for research purposes.

The inclusion criteria were patients with LLL in one or both legs, primary or secondary, and degrees II, III or IV, where degree II is classified as an early edema and IV, severe edema with elephantiasis. A group of medical doctors and physical therapists determined the degree of lymphedema by clinical examination. The first author participated in all assessments. The exclusion criteria were: inability to walk independently, use of walking aids (e.g. crutches), severe orthopedic or neurologic concomitant diseases (e.g. osteoarthritis, lumbar radiculopathy).

Twenty-three patients from the Lymphedema Rehabilitation Unit of the La Fe Hospital volunteered for the study. The demographic and clinical characteristics of the patients are shown in Table 1. These parameters include: age, body mass index (BMI), gender, duration of the disease, number of lymphangitis attacks, absolute leg volume and excess volume in unilateral patients. There was a majority of females, the total median age was 53.1 years (range 17-77), lymphedema was secondary in 13% and primary in 87% of the patients; lymphedema chronicity was 22.9 years; mean baseline EV was 31.6592 ml lower limb lymphedema (LLL).

Clinical assessment

The volume of the limbs was assessed and calculated based on the Kuhnke formula.[20] Tape perimeter measurements were taken starting at the dorsum of the foot, at the ankle and they were repeated every 4 cm in the proximal direction until the hip. The disk model is regarded as the method of choice in clinical practice.[21,22] Excess volume (EV) is the absolute amount of edema which is calculated as the difference between lymphedematous and healthy limb volume in unilateral cases. Patients were classified in 4 groups according to their clinical characteristics (patient type) in order to manage the analysis from a clinical point of view unilateral moderate lymphedema, unilateral severe lymphedema (elephantiasis), bilateral moderate lymphedema and bilateral elephantiasis. It was considered as elephantiasis when the percentage of EV was above 35% from the healthy limb in unilateral lymphedema, and when the volume was above 10 liters in bilateral cases according to previous work.[23]

Experiments and Biomechanical assessment

The patients walked with their preferred flat-sole shoes at self-selected speed on a force plate (NED/IBV AMH, IBV, Valencia, Spain) while the GRF under the foot were recorded in consecutive walking trials. A minimum of five correct foot contacts inside of the platform for each foot were considered.

Table 1. Characteristics of the lymphedema patients

	Total	Unilateral Moderate	Unilateral Severe	Bilateral Moderate	Bilateral
n	23	5	5	6	7
Age (median, range)	53.1 (17-77)	34.3 (17-55)	49.4 (39-77)	53.3 (40-67)	58.9 (45-75)
Gender:					
Male	6 (26.1%)	3 (60%)	2 (40%)	1 (16.7%)	0
Female	17 (73.9%)	2 (40%)	3 (60%)	5 (83.3%)	7 (100%)
Weight (mean, 95%CI)	89.7 (82.4-96.9)	76.4 (62.0-90.8)	88.4 (67.7-109.1)	88.7 (69.7-107.6)	100.9 (92.9-108.9)
BMI (mean, 95%CI)	34.6 (31.9-37.2)	26.4 (24.4-28.3)	32.2 (23.5-40.9)	36.7 (31.8-41.6)	40.3 (37.9-42.7)
Duration (years) (mean, 95%CI)	22.9 (17.4-28.4)	15.5 (6.8-22.2)	20.2 (8.2-32.3)	15.1 (5.2-25.0)	37.4 (26.5-48.3)
Lymphangitis attacks (mean, 95%CI)	7.4 (4.2-10.6)	10.6 (1.4-19.8)	7.4 (2.0-12.8)	0.2 (0.0-0.4)	11.3 (3.4-19.2)
Etiology: (Number, percentage)					
Primary	20 (87%)	4 (80%)	4 (80%)	5 (83.3%)	7 (100%)
Secondary	3 (13%)	1 (20%)	1 (20%)	1 (16.7%)	0
Absolute volume (ml) (mean, 95%CI)	10682 (9474-11889)	9467 (6057-12877)	14490 (8032-20948)	7360 (5986-8734)	13324 (11641-15008)
Excess Volume (ml) in unilateral (mean, 95%CI)	3165 (1587-4743)	1677 (570-2785)	5103 (1246-8960)		
Percentage of EV (mean, 95%CI)	30.4 (20.9-39.9)	21.1 (9.9-32.4)	45.7 (34.3-57.2)		

BMI: Body Mass Index; EV: Excess volume

The patterns of the three components of the GRF were analyzed considering the hypotheses formulated about the potential gait disturbances of patients with lymphedema in the lower limb.

The valid GRF recordings for each subject, distinguishing between healthy and affected legs, were normalized by the body weight and converted to percentage of the stance phase. Then, the recordings were averaged by patient and the following parameters were retained for further analysis: braking and propulsive or pushing peak forces from the A-P component of the GRF as well as the swing and push-off force from the vertical GRF. In addition, the gait speed and the average stance duration for each patient were also recorded.

Statistical analysis

The results of descriptive analysis were presented in terms of central tendency and dispersion (mean, median, 95% confidence interval) for continuous variables, and the absolute and relative frequencies were calculated in the case of categorical variables.

The continuous variables were: gait speed, stance duration, and the GRF parameters normalized to body weight. The categorical variables were: affected limbs (unilateral/bilateral) and severity of lymphedema (severe/moderate).

A one-way ANOVA with LSD post-hoc test of the gait parameters (speed, stance duration and GRF parameters) was performed considering the type of lymphedema as a factor (four levels: unilateral/bilateral and moderate/severe). Only the parameters corresponding to the affected limbs were considered. In addition, the linear tendency between the four categories of lymphedema was analyzed. The data also complied with the requirements for ANOVA that are normality of the data (Kolmogorov-Smirnov test) and homogeneity of variances (Levene's test). If these tests were significant ($p \leq 0.05$) for any analysis of variance we used a non-parametric analysis with Kruskal-Wallis Test and Jonckheere-Terpstra test for the linear tendency analysis. A two-way ANOVA was conducted to compare the GRF parameters of the affected and the healthy limbs and their interaction with lymphedema severity. The SPSS statistical package version 15 (SPSS Inc, Chicago, IL, USA) was used in the patient database and the statistical analysis.

RESULTS

Gait speed was significantly lower in the severe bilateral lymphedema patients than in the other groups, while there were no differences between the remaining three groups. It must be noted that the variability was higher in the patients with severe unilateral lymphedema (Table 2). The analysis of the vertical GRF graphs showed that these forces were more variable in the non-affected leg (Figure 1). While the unilateral patients, either severe or moderate, showed the typical M-shaped pattern of the vertical GRF with two peaks corresponding to weight acceptance and push-off, the bilateral patients showed a flat force pattern that was more evident in the severe cases (Figure 1). The unilateral patients showed a high degree of similarity between affected and non-affected legs. However, the variability in the severe cases was larger especially at the initial loading and push-off peaks.

The M-L GRF were smaller in the non-affected side, while the patterns were similar to those of healthy gait (Figure 2). The patterns of the bilateral moderate indicated more asymmetry and showed larger values with larger variability.

With respect to the A-P GRF, that reflected the forward braking and acceleration of the body center of mass, it must be noted that the patients with bilateral lymphedema showed lower A-P forces (Figure 3).

Relation between GRF parameters of the gait and the type of LLL patient.

There was a significant linear tendency between the four groups of lymphedema patients and the speed (Table 2), the gait was slower when the lymphedema was more severe and affected both limbs.

The stance phase duration was significantly longer in patients with bilateral and severe lymphedema than in the other groups. For the lymphedematous limbs, it was observed a significant linear tendency between the groups of lymphedema patients and the braking force normalized to the subject weight, the pushing force and push-off (Table 2). No differences were found between the groups with respect to the mid-stance forces.

The braking force was lower when lymphedema affects both limbs and was more severe, and pushing as well as push-off also decreased in bilateral and severe cases. A detailed analysis of the GRF of typical cases of each LLL revealed interesting patterns.

Unilateral severe (elephantiasis)

Regarding the A-P forces, both legs showed high degree symmetry: the curves of the right and left legs were very similar and relatively small (Figure 3). The M-L force components show a clear asymmetry between the affected and the non-affected limb that has a lower magnitude (Figure 2).

The vertical GRF were symmetric between the right and left legs (Figure 1). The affected leg showed an impulsive load during heel contact reflected in the peak of the vertical force

Table 2. Relation between the gait and ground reaction force parameters and the type of lymphedema

	Gait parameters (mean, 95%CI)	Unilateral moderate	Unilateral severe	Bilateral moderate	Bilateral severe	P value of LTd
All	Speed (m/s)	1.02 (0.88-1.17)	0.97 (0.78-1.16)	0.91 (0.76-1.06)	0.45 (0.27-0.63)	p<0.0001[b,c,d]
	Stance time (s)	0.78 (0.71-0.86)	0.78 (0.73-0.84)	0.75 (0.67-0.82)	0.91 (0.85-0.97)	p=0.019 [b,c,d]
Only in lymphedematous limbs	Braking force (A-P)	0.18 (0.09-0.27)	0.17 (0.10-0.23)	0.12 (0.10-0.15)	0.08 (0.06-0.10)	p<0.0001[a,b,c,d]
	Pushing force (A-P)	0.18 (0.11-0.25)	0.16 (0.08-0.25)	0.16 (0.12-0.19)	0.08 (0.06-0.10)	p=0.001[b,c,d]
	Push- off (Vertical)	1.09 (1.01-1.18)	1.07 (0.93-.1.21)	0.99 (0.93-1.06)	0.99 (0.97-1.00)	p=0.018[a,b,c]
	Mid-stance (Vertical)	0.82 (0.71-0.92)	0.81 (0.69-0.94)	0.80 (0.73-0.87)	0.84 (0.76-0.93)	p=0.79

LTd: Linear tendency; [a]significance in multiple comparison test between unilateral moderate and bilateral moderate; [b]significance in multiple comparison test between unilateral moderate and bilateral severe; [c]significance in multiple comparison test between unilateral severe and bilateral severe; [d]significance in multiple comparison test between bilateral moderate and bilateral severe.

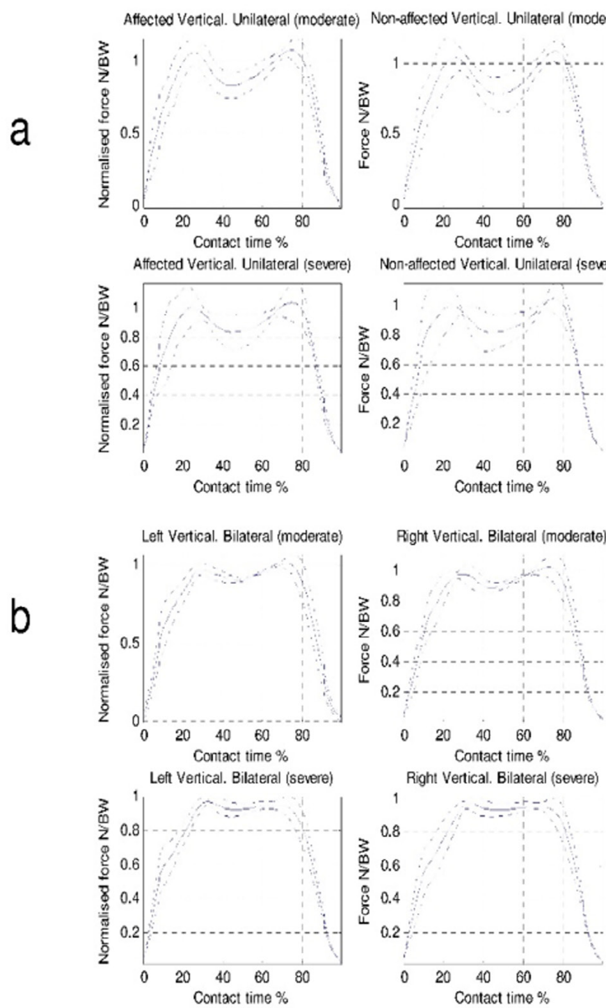

Figure 1. Average GRF recordings (a) unilateral, (b) bilateral of the vertical forces from patients with (a) unilateral and (b) bilateral lymphedema grouped by severity per the clinical assessment: Moderate (upper graph) and severe (lower graph) for both limbs: affected (left side) and non-affected (right side). Forces are normalized with regarding body weight (N/BW). The solid line indicates mean and the dotted lines the standard deviations.

loading. It must be noted that the curve was not as "flat" as in the bilateral case, but the valley occurring during single stance was not very evident.

Bilateral lymphedema

Gait was slow and the vertical GRF pattern was flat in both legs, not showing the typical 2-peak shape (see Figure 1). Large M-L forces were found (see Figure 2).

DISCUSSION

GRF patterns

Patients with lymphedema showed distinct gait patterns (GP) as reflected in the ground reaction forces (GRF) during gait. They presented large vertical force loads with elevated rate of loading and high foot contact peaks. This was due to the large weight of the patients and, particularly, to the high weight of the limb. In addition, they showed a cautious GP, characterized by slow speed and short steps with long stance time. The data suggested that the most important factor impairing gait was related to lymphedema affecting one (unilateral) or both limbs (bilateral) and, afterwards, to the level of severity.

The vertical GRF showed clear patterns in which the normal M-shape was becoming more and more flat on the bilateral patients depending on the severity. This flat pattern is typical of people walking at low speeds that do not transfer abruptly the weight from one leg to the other during double stance.[1] Usually, steps are shorter and the low gait speed is due to the longer duration of the double stance phase. Although this was the case for the severe bilateral patients, the moderate bilateral cases had no speed differences with the other groups (moderate and severe unilateral). However, it must be noted that all lymphedema patients walked, on average, at slower speed, as compared to values obtained from healthy adult populations.[12,16,24] These data can be compared with those obtained from the gait of obese people.[17] The volume and weight increase of the affected edematous limb, results in an overweight. Due to this overweight, the gait patterns of obese patients could be similar to the lymphedema patients. Stance time and speed in study of Spyropoulos et al.[17] were, respectively, 0.77 s and 1.09 m/s in obese people, and 0.64 s and 1.64 m/s in non-obese. These values are similar to those found in our study. The lowest mean value of stance time was 0.75 s in bilateral moderate and the largest one was 0.91 s

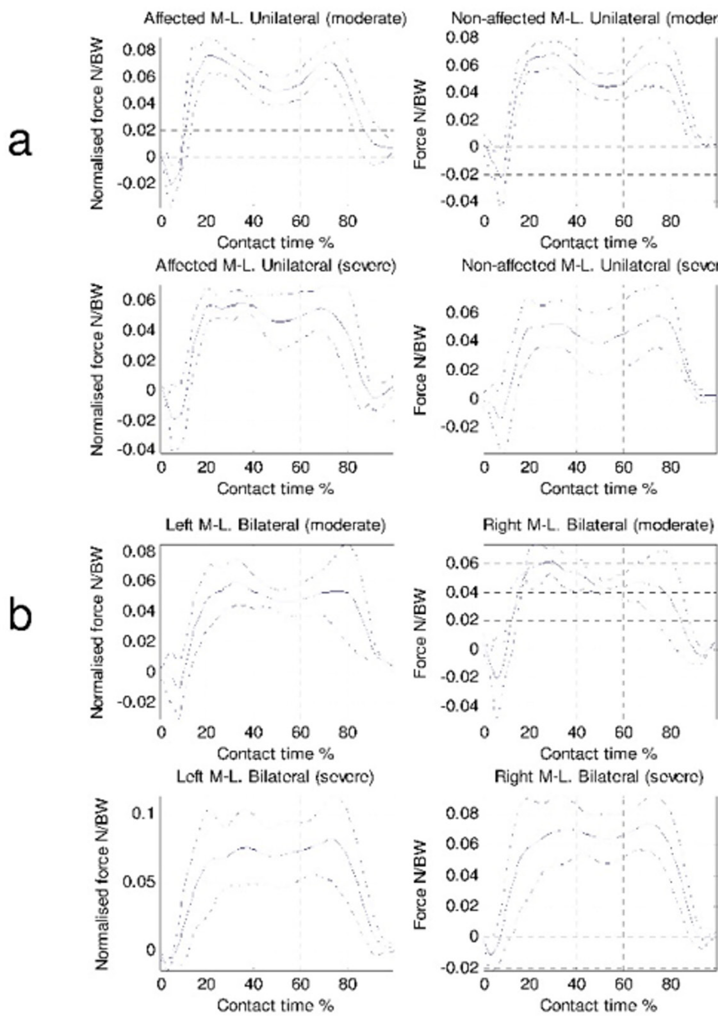

Figure 2. Average GRF recordings (a) unilateral, (b) bilateral of the mediolateral (M-L) forces from patients with (a) unilateral and (b) bilateral lymphedema grouped by severity per clinical assessment: Moderate (upper graph) and severe (lower graph) for both limbs: affected (left side) and non-affected (right side). Forces are normalized regarding body weight (N/BW). The solid line indicates mean and the dotted lines the standard deviations.

in the bilateral severe lymphedema; the speed ranged from 0.45 (bilateral severe) to 1.02 m/s (unilateral moderate), as shown in Table 2. The sample of patients with lymphedema had a high body mass index (BMI) and some of them could be classified as obese. The lymph accumulation could be a confounding factor of obesity that must be considered in future studies. First, the excess of mass, either fat or lymph, is distributed differently in obese and LLL patients. While the excess of mass in LLL patients is distal, that is concentrated in the leg(s), in obese patients, either gynoid or android, the mass excess is more proximal to the center of the body. Second, there is an interaction between lymphedema and obesity, and it has been reported that an excess of fat causes inflammatory processes that affects the lymphatic vessels function.[25-27]

It can also be hypothesized that the fact that the unilateral cases, either moderate or severe, showed vertical GRF patterns close to normal, could be attributed to a compensating mechanism with the non-affected leg. It must also be noted that the "flat" shape of these forces could be related to a significantly slower walking speed, such as in the severe bilateral cases.

The M-L forces are related to gait stability and to the width of base of support. As the M-L forces are directed to the median plane of the body, left and right feet have opposite directions. Larger excursions in these forces suggest that gait is performed with a broader base of support and larger inclinations of the body center of mass to the frontal plane. This can be seen in the unilateral cases, where the M-L forces of the affected limb are higher. The larger lateral inclination of the body could be related to a mechanism to improve stability.

GRF parameters

Several GRF parameters of LLL patients reported in this study are very similar to the values found in obese[16] and different from the values of non-obese population.[28] The vertical push off in bilateral groups (0.99) was lower than the values found in normal population (1.11) and even lower than those found in obese people (1.05). A similar aspect occurred with the A-P pushing force. In this case, the bilateral severe lymphedema patients (0.08) showed lower values than obese subjects (0.19), whereas the value differences in the other lymphedema groups were not as evident (0.18 and 0.16 in the unilateral moderate and severe, respectively, as show in Table 2).

Case study 1: Unilateral Severe

The M-L forces were not symmetric and they were larger in the affected leg. This indicated a GP with large M-L acceleration of the center of mass (COM) possibly related to trunk inclination and stability. It might be regarded as less stable because the COM is accelerated in the M-L axis asymmetrically, for instance with large trunk oscillations in the frontal plane, making the person more prone to fall sideways.

The vertical GRF were very symmetric between the right and left legs (see Figure 1). This indicates that there were compensatory mechanisms of gait. The affected leg showed an impulsive load during heel contact due to the high weight of the leg. This was reflected in the peak of the vertical force loading. It must be noted that the curve was not as "flat" as in the bilateral case, but the valley occurring during single stance was not as evident as in the normal cases. This suggested that, like in the bilateral patients, the steps are of relatively short length with prolonged double stance phases.

Case study 2: Bilateral lymphedema

Gait was slow and the vertical GRF pattern was flat in both legs, not showing the typical 2-peak shape (see Figure 1). This might be related to flat foot with reduced ankle mobility. It was unclear if the mobility of the ankle was

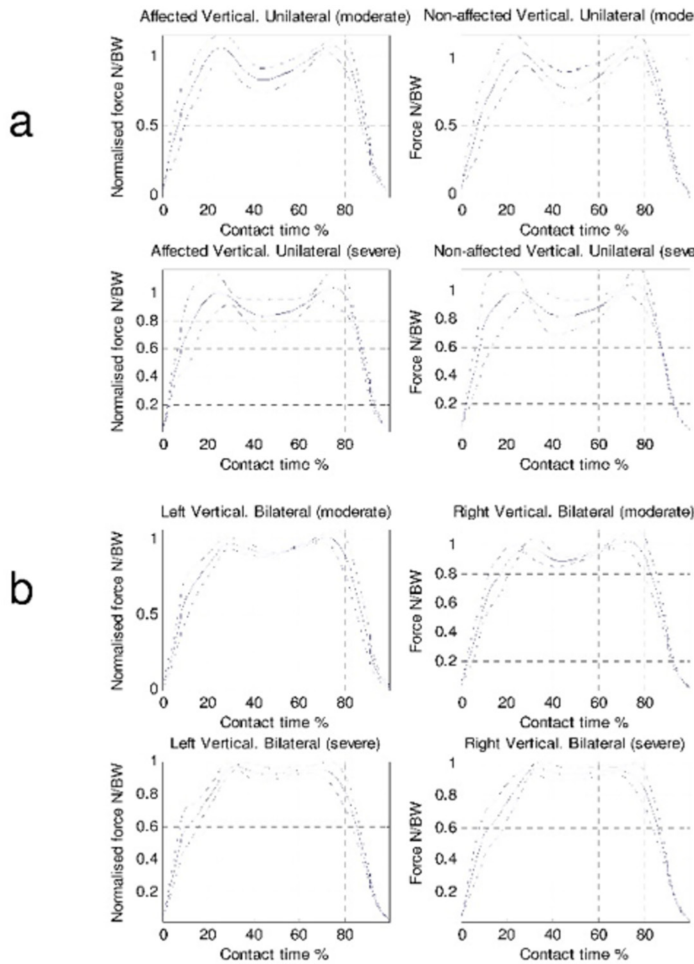

Figure 3. Average GRF recordings (a) unilateral, (b) bilateral of the anteroposterior (A-P) forces from patients suffering (a) unilateral and (b) bilateral lymphedema grouped by severity per clinical assessment: Moderate (upper graph) and severe (lower graph) for both limbs: affected (left side) and non-affected (right side). Forces are normalized regarding body weight (N/BW). The solid line indicates mean and the dotted lines the standard deviations.

reduced due to the edema or it was mechanism to minimize the excessive loads at weight-bearing and take-off caused by the weight of the patient. Therefore, it seems that, as a mechanism to minimize the GRF, the patient walked very slowly. Finally, the large M-L (see Figure 2) forces found in the study may be related to an increased base of support (due to the large volume of the leg) with slow gait speed, suggesting gait stability problems.

In general, it can be stated that gait disturbances worsened with the increase of BMI. In the present study, and in agreement with previous articles regarding obese people,[12] the lowest gait speed, vertical and AP push off forces were found in bilateral severe group.

It is possible that edema may modify the range of motion of the joints; therefore, for future studies it is suggested to evaluate the range of motion of the joints of patients with lymphedema along with a complete analysis of the gait patterns measuring motion and the GRF with two force plates.

Some of the possible consequences of the altered GRF patterns could be related to articular degeneration due to large impulsive loads, gait stability problems and risk of falling. It must be noted that the cautions GP described here has certain similarities with the idiopathic senile gait, associated to the elderly at risk of falling.[12,13] In this respect, it seems sensible to study the incidence of falls in the patients with lymphedema.

CONCLUSIONS

Gait of lower limb lymphedema patients was slower with shorter steps resembling gait of obese patients. Unilateral lymphedema showed asymmetry in the M-L forces, with higher GRF variability in the severe cases. Bilateral lymphedema results in lower A-P forces. Stance phase duration was longer in patients with bilateral and severe lymphedema.

Author Disclosure Statement

The authors have no financial interests in the study or any other type of interest conflict to disclose.

REFERENCES

1. Perry J. Gait analysis: normal and pathological function. Thorofare: Slack; 1992. DOI: http://dx.doi.org/10.1097/01241398-199211000-00023
2. Vaughan CL, Davis BL, O'Connor JC. Dynamics of human gait. 2nd ed. Cape Town: Kiboho; 1999.
3. Collado-Vázquez S. Plataformas dinamométricas. Aplicaciones. Biociencias.2005;3:1-18.
4. Forner Cordero A, Koopman HFJM, van der Helm FCT. Use of pressure insoles to calculate the complete ground reaction forces. J Biomech. 2004;37(9):1427-32. DOI: http://dx.doi.org/10.1016/j.jbiomech.2003.12.016
5. Földi E, Földi M. Lymphostatic diseases. In: Földi M, Földi E, Kubik S. Textbook of lymphology for physicians and lymphedema therapists. Munchen: Urban & Fisher; 2003. p. 231-319.
6. International Society of Lymphology. The diagnosis and treatment of peripheral lymphedema. Consensus document of the International Society of Lymphology. Lymphology. 2003;36(2):84-91.
7. Lenschow E, Schuchhardt C. What mistakes can be made in lymphedema diagnosis in the assessment of accompanying orthopedic diseases? Lymphol Forsch Prax. 2005;9(2):109-12.
8. Robinson MH, Spruce L, Eeles R, Fryatt I, Harmer CL, Thomas JM, et al. Limb function following conservation treatment of adult soft tissue sarcoma. Eur J Cancer. 1991;27(12):1567-74. DOI: http://dx.doi.org/10.1016/0277-5379(91)90417-C
9. Strossenreuther RHK. Guidelines for application of MLD/CDT for primary and secondary lymphedema and other selected pathologies. In: Földi M, Földi E, Kubik S. Textbook of lymphology for physicians and lymphedema therapists. Munchen: Urban & Fisher; 2003. p. 395-403.
10. Aggithaya MG, Narahari SR, Ryan TJ.Yoga for correction of lymphedema's impairment of gait as an adjunct to lymphatic drainage: A pilot observational study. Int J Yoga. 2015;8(1):54-61. DOI: http://dx.doi.org/10.4103/0973-6131.146063
11. Forner-Cordero I, Forner-Cordero A, Maldonado-Garrido D, Cervera-Deval J. Biomechanical study of the gait in patients with lower limb lymphoedema. Eur J Lymphology. 2009;20:1-6.
12. Ko S, Stenholm S, Ferrucci L. Characteristic gait patterns in older adults with obesity--results from the Baltimore Longitudinal Study of Aging. J Biomech. 2010;43(6):1104-10. DOI: http://dx.doi.org/10.1016/j.jbiomech.2009.12.004

13. LaRoche DP, Kralian RJ, Millett ED. Fat mass limits lower-extremity relative strength and maximal walking performance in older women. J Electromyogr Kinesiol. 2011;21(5):754-61. DOI: http://dx.doi.org/10.1016/j.jelekin.2011.07.006
14. Freedman Silvernail J, Milner CE, Thompson D, Zhang S, Zhao X. The influence of body mass index and velocity on knee biomechanics during walking. Gait Posture. 2013;37(4):575-9. DOI: http://dx.doi.org/10.1016/j.gaitpost.2012.09.016
15. Page Glave A, Di Brezzo R, Applegate DK, Olson JM. The effects of obesity classification method on select kinematic gait variables in adult females. J Sports Med Phys Fitness. 2014;54(2):197-202.
16. Lai PP, Leung AK, Li AN, Zhang M. Three-dimensional gait analysis of obese adults. Clin Biomech (Bristol, Avon). 2008;23 Suppl 1:S2-6. DOI: http://dx.doi.org/10.1016/j.clinbiomech.2008.02.004
17. Spyropoulos P, Pisciotta JC, Pavlou KN, Cairns MA, Simon SR. Biomechanical gait analysis in obese men. Arch Phys Med Rehabil. 1991;72(13):1065-70.
18. Westlake CG, Milner CE, Zhang S, Fitzhugh EC. Do thigh circumference and mass changes alter knee biomechanics during walking? Gait Posture. 2013;37(3):359-62.
19. Castro MP, Abreu SC, Sousa H, Machado L, Santos R, Vilas-Boas JP. In-shoe plantar pressures and round reaction forces during overweight adults' over ground walking. Res Q Exerc Sport. 2014;85(2):188-97.
20. Kurz I. Textbook of Dr. Vodder's manual lymph drainage. In: Harris RS. Therapy. 2nd ed. Heidelberg: Karl S. Haug; 1989. p.124.
21. Chen YW, Tsai HJ, Hung HC, Tsauo JY. Reliability study of measurements for lymphedema in breast cancer patients. Am J Phys Med Rehabil. 2008;87(1):33-8. DOI: http://dx.doi.org/10.1097/PHM.0b013e31815b6199
22. Deltombe T, Jamart J, Recloux S, Legrand C, Vandenbroeck N, Theys S, et al. Reliability and limits of agreement of circumferential, water displacement, and optoelectronic volumetry in the measurement of upper limb lymphedema. Lymphology. 2007;40(1):26-34.
23. Forner-Cordero I, Muñoz-Langa J, DeMiguel-Jimeno JM, Rel-Monzo P. Physical therapies in the treatment of lymphedema: preliminary results of a phase III, multicenter, randomized, double-blind, controlled study [abstract]. Eur J Lymphol Relat Probl. 2008;19(54):6. [Presented at XXXIV ESL Congress; 2008 June 25-27; Naples, Italy].
24. RunhaarJ, Koes BW, Clockaerts S, Bierma-Zeinstra SM. A systematic review on changed biomechanics of lower extremities in obese individuals: a possible role in development of osteoarthritis. Obes Rev. 2011;12(12):1071-82. DOI: http://dx.doi.org/10.1111/j.1467-789X.2011.00916.x
25. Ching DL, Anderson A, Kumarasinghe SP. Lower limb lymphoedema and obesity: a much-neglected association. Br J Hosp Med (Lond). 2015;76(9):542-3. DOI: http://dx.doi.org/10.12968/hmed.2015.76.9.542
26. O'Malley E, Ahern T, Dunlevy C, Lehane C, Kirby B, O'Shea D. Obesity-related chronic lymphoedema-like swelling and physical function. QJM. 2015;108(3):183-7. DOI: http://dx.doi.org/10.1093/qjmed/hcu155
27. Mehrara BJ, Greene AK. Lymphedema and obesity: is there a link? Plast Reconstr Surg. 2014 Jul;134(1):154e-160e. DOI: http://dx.doi.org/10.1097/PRS.0000000000000268
28. Chao EY, Laughman RK, Schneider E, Stauffer RN. Normative data of knee joint motion and ground reaction forces in adult level walking. J Biomech. 1983; 16(3):2 DOI: http://dx.doi.org/10.1016/0021-9290(83)90129-X