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Effect of the 6-minute walk test on plantar loading and capability to produce ankle plantar flexion forces

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ABSTRACT

The six-minute walk test (6MWT) is used to evaluate the ambulatory capacity of patients suffering from respiratory disorders, obesity or neuromuscular diseases. Our primary aim was to evaluate the effects of the 6MWT on the postural sway and the ankle plantar flexion forces in healthy subjects.

We measured the ankle plantar flexion forces and the plantar contact area before and after a 6MWT in normal weight and overweight subjects with no history of respiratory, cardiac, and neuromuscular disorders. A post-6MWT sensation of bodily fatigue was evaluated by Multidimensional Fatigue Inventory (MFI) and Pichot fatigue scales. A computerized pedobarographic platform was used to collect the mean plantar contact area, the changes of the center of pressure (CoP) surface and its medial and lateral deviations. In a limited number of subjects, the reproducibility of all the measurements was explored.

In both groups, the 6MWT elicited a sensation of bodily fatigue. It also significantly reduced the ankle plantar flexion forces, and increased both the mean plantar contact area and the CoP surface, the changes being not apparent after 10 min. The post-6MWT lateral CoP deviations were accentuated in normal weight subjects, while an increase in medial CoP deviations occurred in overweight ones. The 6MWT-induced changes in the plantar flexion force and pedobarographic variables were reproducible.

Because this study clearly showed some post-6MWT alterations of the subjects' posture sway of our subjects, we questioned the possible mechanisms occurring that could explain the altered muscle force and the transient destabilization of posture after the 6MWT.

1. Introduction

The six-minute walk test (6MWT) was primarily proposed to explore the cardiorespiratory response of patients suffering from respiratory disorders. As stated by the American Thoracic Society (ATS) [1], "the 6MWT measures the distance that a patient can quickly walk on a flat, hard surface in a period of 6 minutes. It evaluates the global and integrated responses of all the systems involved during exercise, including the pulmonary and cardiovascular systems, systemic circulation, neuromuscular units, and muscle metabolism. . ..Because most activities of daily living are performed at submaximal levels of exertion, the 6MWT reflects the functional exercise level for daily physical activities."

More recently, the 6MWT was also proposed to explore patients with overweight [2–7], sarcoidosis [8,9], multiple sclerosis [10,11], and spinal muscular atrophy [12–14]. Despite "the 6MWT reflects the functional exercise level for daily physical activities" [1], bodily fatigue often occurs after the 6MWT in patients. The evaluation of bodily fatigue was often based on Borg visual analogic scale, and few studies used the Fatigue Assessment Scale questionnaire [8] or the Hammersmith Functional Motor Scale-Expanded [13]. Post-6MWT muscle fatigue was suspected because a reduction of the quadriceps [8], knee flexor, and hip abductor [12] peak muscle strength was reported. However, the ankle plantar flexion forces were never measured despite they represent a more appropriate index of fatigue of the leg muscles which control the foot motion. Moreover, the consequences of the 6MWT on posture were never examined. Hypothesizing that the 6MWT could induce a leg muscle fatigue, a transient destabilization of the posture may also

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be suspected. Several studies have already reported an increased surface of the center of pressure (CoP) after a maximal running exercise [15] and a maximal sustained foot inversion [16], as well as an increased amplitude of CoP deviations after an intensive marching [17] and a high-heeled gait [18].

Our aim was to evaluate the effects of the 6MWT on the ankle plantar flexion forces and on the plantar loading in healthy subjects. We compared subjects with normal weight as well as overweight subjects because numerous previous studies have shown that overweight individuals often have difficulties to stabilize their posture [19], increasing both the medial and the lateral CoP deviations [6,19–21].

2. Materials and methods

2.1. Subjects

Our institutional review board for human studies (CPP Sud Mediterranee 1) approved the protocol and written consent was obtained from the subjects. Thirteen female and eleven male subjects (mean age: 35 ± 6 y) were studied. Twelve had a body mass index (BMI) in a normal range and the others were overweight (Table 1). The podiatrists solely included in this study the subjects who had no major foot malalignment. Some of them had a hallus abducto valgus ($n = 4$) or planus feet ($n = 5$). None of the subjects were involved in an exercise program and some of them (8/24) occasionally practiced sport activities (jogging, tennis) for less than 3 h a week. A light meal was acceptable before the early morning or early afternoon 6MWT tests. Despite the subjects were self-reported healthy, to respect the statement by the American Thoracic Society [1], we examined contraindications for the 6MWT which included the following: a resting heart rate (HR) of more than 100 bpm, a systolic blood pressure of more than 170 mmHg, a diastolic blood pressure of more than 100 mmHg, and a percutaneous oxygen saturation (SpO_2) of less than 96%. A pulse oximeter (Spengler Oxy Led, Sofamed, France) gave the instantaneous values of SpO_2 and HR and the blood pressure was measured with a sphygmomanometer (Omron RS3, *OMRON* Sante, Rosny sous Bois, France).

2.2. Pedobarographic measurements

The subjects were bare-footed when standing in double limb stance on the pedobarographic platform for 30 s. The computerized 530 mm × 600 mm strain-gauge platform (WinPOD, Medicapteurs SA, Toulouse, France) consisted of 2304 resistive load cells and its sampling frequency was 100 images s^{-1}. We measured the peak and mean foot pressures, the mean plantar contact area, the ratio of forefoot/rearfoot surfaces, and the CoP surface. The maximum lateral/medial CoP deviations were measured by displacing cursors on the screen of the computer.

Table 1
Morphological and physiological characteristics of normal and overweight subjects at inclusion in the study. BMI: body mass index; SpO_2: percutaneous oxygen saturation. CoP: center of pressure. Values are the mean ± SEM. Symbol # denotes significant intergroup differences ($^{\#}p < 0.05$; $^{\#\#}p < 0.01$; $^{\#\#\#}p < 0.001$).

	Normal weight	Overweight
Number	10	12
Age, y	35 ± 5	39 ± 4
Weight, kg	66 ± 3$^{\#\#\#}$	88 ± 4
BMI, kg m^{-2}	22 ± 1$^{\#\#\#}$	30 ± 1
Systolic blood pressure, mmHg	129 ± 4	137 ± 4
Heart rate, bpm	82 ± 5	90 ± 4
SpO_2, %	98 ± 1	97 ± 1
Maximal ankle plantar flexion force, *N*		
Right foot	140 ± 10$^{\#\#}$	190 ± 10
Left foot	138 ± 15$^{\#\#}$	200 ± 10
Peak plantar pressure, N cm^{-2}	13.0 ± 0.5$^{\#\#\#}$	16.2 ± 0.4
Mean plantar pressure, N cm^{-2}	4.7 ± 0.2$^{\#\#}$	5.6 ± 0.3
Mean plantar contact area, cm^2	162 ± 9$^{\#}$	192 ± 8
Ratio forefoot/rearfoot area	0.97 ± 0.12$^{\#}$	0.63 ± 0.05
CoP surface, mm^2	169 ± 43$^{\#\#}$	355 ± 37
CoP medial deviation, mm	3.9 ± 0.3$^{\#}$	5.2 ± 0.4
CoP lateral deviation, mm	2.1 ± 0.2$^{\#}$	2.9 ± 0.3

2.3. Measurement of the ankle plantar flexion forces

The maximal ankle plantar flexion forces (F_{max}) were measured under isometric conditions using a custom-built device (Fig. 1A). The subjects were seated on a chair with the ankle in a neutral position (95°) when the foot was positioned on the foot plate of the dynamometer. The foot plate was articulated around a horizontal axis allowing only ankle plantar flexion in the sagittal plane. The distal part of the articulated support was connected to a vertically positioned load cell (Scaime model ZF 100, AS Technologies, Langlade, France: linear from 0 to 1000 N). The subjects had no feedback of the developed force and they were also not informed of the reference values so as not to influence their performance after the 6MWT. Before the 6MWT challenge, three 5-s maximal ankle plantar flexion maneuvers were executed by each leg to determine F_{max} values.

2.4. The 6MWT

A "warm-up" period consisting in a first 6MWT was performed 1 h before a second 6MWT during which all the measurements were considered. This practice walk was recommended by the American Thoracic Society [1]. The 6MWT was performed indoors, along a long, flat, straight 40-m corridor whose length was marked every 5 m. Turnaround points were marked with a cone. The required equipments were: a stopwatch, a pulse oximeter, a sphygmomanometer, the Multidimensional Fatigue Inventory (MFI) [22] and Pichot [23] bodily fatigue scales (both validated for French subjects), a source of oxygen and an automated electronic defibrillator. The subjects were asked to walk, and not run, as far as possible for 6 min, back and forth in the hallway. They were permitted to slow down, to stop, and to rest as necessary.

2.5. Protocol

- *Before the 6MWT*: measurements of SpO_2, HR, and arterial blood pressure, maximal ankle plantar flexion force of each foot (3 measurements), and pedobarographic measurements.
- *During the 6MWT*: SpO_2 and HR were measured every min.
- *Post-test measurements*: (1) calculation of the total distance walked, rounding to the nearest meter; (2) measurement of SpO_2, HR, arterial pressure, F_{max} for each foot, pedobarography, and estimation of the post-walk fatigue level using the Pichot and MFI scales. After the 6MWT had stopped, the peak value of the ankle plantar flexion force was measured during the first min. Then, the subject stayed on the pedobarographic platform during the next 2 min. Thus, the successive measurement of the force and pedobarographic variables maximally occurred within 3 min and the subject answered the questionnaire during the further 2 min. The first series of measurements was called R0. Then, F_{max} and pedobarographic measurements were repeated at 10 (R10), and 20 min (R20). In some overweight subjects, a modest SpO_2 decrease occurred at the end of the 6MWT but the oxygen saturation recovered normal (control) values within the first min of the post-6MWT period.

The total distance walked was compared to normal values for women and men [24].

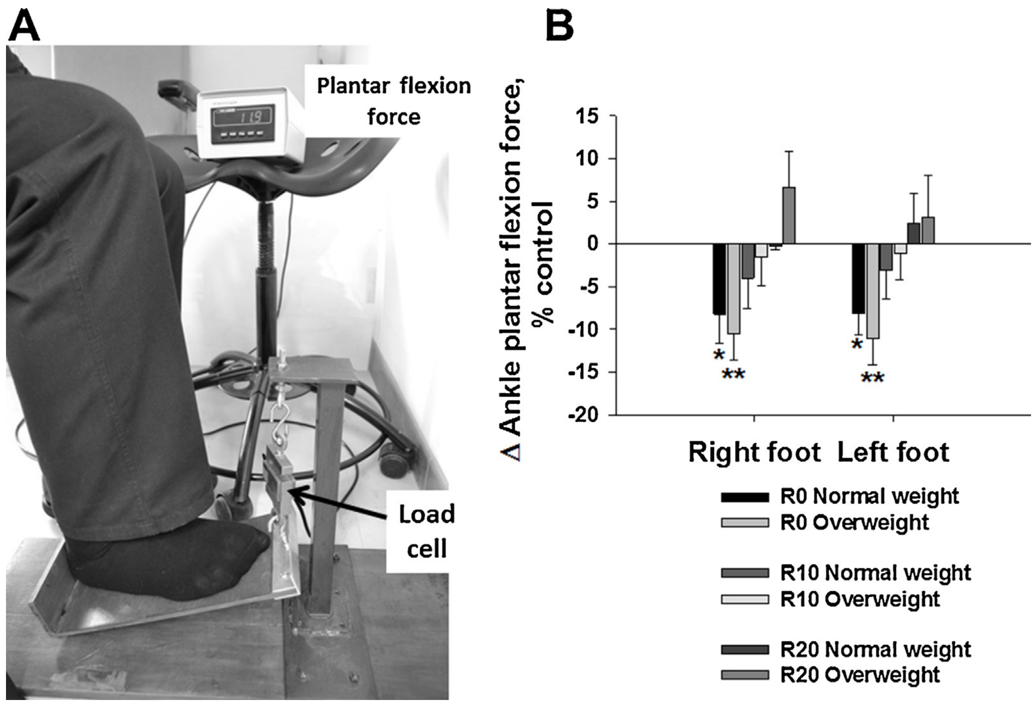

Fig. 1. Measurement of the ankle plantar flexion force. (A) The custom-built apparatus used to measure the peak plantar flexion force using a load cell. The subject had no feedback of the produced force. (B) Relative changes in peak ankle plantar flexion force measured after the 6 min walk distance test (6MWT) in both feet of normal and overweight subjects. Asterisks denote significant changes from reference value measured before the 6MWT (*$p < 0.05$; **$p < 0.01$).

The morphological and physiological characteristics of normal and overweight subjects are reported in Table 1.

The reproducibility of the data measured during and after the 6MWT was assessed in 10 subjects with normal weight by repeating the measurements 30 days after the first challenge.

2.6. Statistical analyses

Data are presented as mean ± one standard error of mean (SEM). The normal distribution of the variables was verified with the Kolmogorov–Smirnov test. For temporally repeated data, the changes over time were determined using ANOVA for repeated measures when the variables were normally distributed or a Friedman's test for repeated measures when they were not. Time differences were identified using the Tukey's multiple comparison test. Least square regression analyses were used to compare post-6MWT changes in plantar flexion force and pedobarographic variables with the scores of fatigue scales. Significance was accepted if $p < 0.05$.

3. Results

As shown in Table 1, compared to data measured in normal weight individuals, the overweight subjects had higher levels of maximal ankle plantar flexion force, of mean plantar pressure and surface, of mean CoP surface, and of medial and lateral CoP deviations, but their forefoot/rearfoot surface ratio was lower. The mean plantar contact area and pressure were proportional to BMI: mean plantar contact area = 67.7 + 4.3 × BMI, $r = 0.573$, $p < 0.01$; mean plantar pressure = 2.9 + 0.1 × BMI, $r = 0.593$, $p < 0.01$.

The 6MWT distance was significantly lower in overweight subjects (533 ± 26 m, i.e., 92 ± 4% of predicted values) compared to subjects having a normal weight (639 ± 31 m, i.e., 97 ± 1% of predicted values). Both the Pichot and MFI fatigue scales indicated a higher perception of bodily fatigue (Fig. 2). The HR variations at the end of the 6MWT were significantly higher in overweight individuals (ΔHR = +35 ± 6 bpm compared to +8 ± 7 bpm in normal weight subjects, $p < 0.01$) and they also had a tendency to a modest SpO_2 decrease.

After the 6MWT had stopped, we measured in all subjects a significant decrease in the ankle plantar flexion forces of both feet at R0 but these changes did not exist anymore after 10 min (Fig. 1B). No significant differences were found between the normal weight subjects ($\Delta F_{max} = -8 + 4\%$) and the overweight ones ($\Delta F_{max} = -11 + 5\%$) (Fig. 1B). Also, the mean plantar contact area significantly increased after the 6MWT in both groups of subjects ($p < 0.01$) but in a modest proportion (+6 + 1%), while the CoP surface markedly increased (Fig. 3A) (+34 ± 12% in the normal weight subjects and +29 ± 10% in the overweight ones). An accentuation of the CoP deviations occurred in both groups (Fig. 3B): the lateral CoP deviations increased in normal weight subjects (+46 ± 10%) whereas the medial (anterior–posterior) CoP deviations (+31 ± 9%) were accentuated in the overweight individuals. The ratio between the forefoot and rearfoot surfaces did not significantly vary in both groups. All the changes in F_{max} and CoP deviations were not apparent after 10 min.

The 6MWT was repeated after a 30-day delay in 10 subjects having a normal weight. Table 2 shows no significant differences between data collected at D0 and D30 with respect to the 6MWT distance, the bodily fatigue scores, and the post-6MWT changes in ankle plantar flexion forces and pedobarographic variables.

No correlation was found between the bodily fatigue scale indexes and the magnitude of post-6MWT changes in the ankle plantar flexion force and the pedobarographic variables.

4. Discussion

4.1. Main data

The sensation of a bodily fatigue after the 6MWT was confirmed by two fatigue scales (Pichot and MFI) and it was accentuated in overweight subjects. The 6MWT elicited a modest but significant decrease of the ankle plantar flexor forces and it was associated

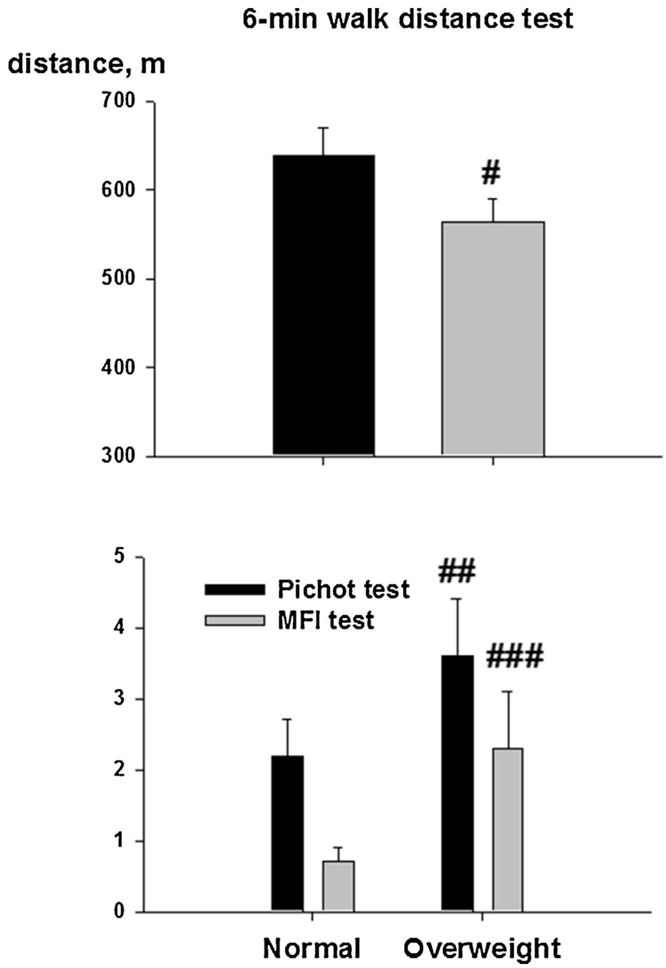

Fig. 2. The 6-min walk distance test. Lower distance value was measured in overweight subjects and their bodily fatigue sensation estimated by the Pichot and MFI fatigue scales was higher. Symbol # denotes significant intergroup difference ($^{\#}p < 0.05$; $^{\#\#}p < 0.01$; $^{\#\#\#}p < 0.001$).

with posture changes, characterized by an increase in both the mean plantar contact area and CoP surface and an accentuation of the maximal CoP deviations. The 6MWT-induced changes in the ankle plantar flexion force as well as the pedobarographic variables were highly reproducible.

4.2. Limitations of the study

We only measured post-6MWT CoP deviations and a modest increase in the mean plantar contact area. Previous studies [17,18] have shown that the measurement of the maximal CoP deviations constituted a more valuable index of posture destabilization than an increased plantar surface. It is well known that the maximal force a muscle produces depends on the length of the muscle and therefore on the position of the joint the muscle crosses. This has been verified for the measurement of isometric ankle plantar flexion [25–28]. In our study, the knee angle was fixed at 98° to limit leg extension during the plantar flexion and the ankle angle was fixed at 95°. Our homemade apparatus used to measure the ankle plantar flexion force did not allow to adjust the ankle angle, but in each individual the angles of knee, ankle, and metatarsal phalangeal joints were the same before and after the 6MWT. Thus, the post-6MWT changes found in the maximal ankle plantar flexion forces cannot have been influenced by any change in muscle length.

Table 2
Comparison between 6MWT performances repeated at a 30 day interval in 10 normal weight subjects. Control values (before 6MWT) and their relative changes measured immediately (R0) after the 6MWT, expressed in percentage of pre-6MWT data, are reported. Values are the mean ± SEM. Asterisk indicates that the post-6MWT changes are significant (*$p < 0.05$). No significant difference was noted between D0 and D30.

	D0	D30
Distance, m	703 ± 64	673 ± 42
Pichot scale	1.8 ± 0.6	0.6 ± 0.4
MFI scale	0.4 ± 0.1	0.2 ± 0.1
Ankle plantar flexion force, *N*		
Right foot	140 ± 10	164 ± 6
Left foot	138 ± 15	140 ± 10
ΔAnkle plantar flexion force, %		
Right foot	−8 ± 5*	−10 ± 4*
Left foot	−9 ± 4*	−11 ± 5*
Peak plantar pressure, N cm^{-2}	13.0 ± 0.5	13.8 ± 0.7
Mean plantar pressure, N cm^{-2}	4.7 ± 0.2	4.7 ± 0.2
Mean plantar contact area, cm^2	162 ± 9	164 ± 9
ΔPlantar contact area, %	+6 ± 1	+5 ± 2
CoP surface, mm^2	169 ± 43	173 ± 33
ΔCoP surface, %	+16 ± 12	+9 ± 15
CoP medial deviation, mm	3.9 ± 0.3	4.2 + 0.5
ΔCoP medial deviation, %	+19 ± 8	+14 ± 6
CoP lateral deviation, mm	2.1 ± 0.2	2.4 ± 0.3
ΔCoP lateral deviation, %	+58 ± 12*	+63 ± 6*

4.3. Comparison with literature data

Our study confirmed previous pedobarographic observations in obese subjects. Indeed, our static pedobarographic evaluation showed higher values of the total plantar contact area. Also, the peak plantar pressure was positively correlated with the BMI as in the study by Birtane and Tuna in obese subjects [2]. De Souza et al. [6] also measured an increase in the CoP surface in obese individuals and other studies reported that obese patients had difficulties to stabilize their posture at the beginning of prolonged standing task, increasing both the medial and lateral CoP deviations [6,7].

A bodily fatigue induced by the 6MWT was most often evaluated by the visual Borg analogic scale [1] and more descriptive fatigue scales, like the Pichot and MFI tests, were not previously used. Very few studies have evaluated objective indices of a muscle fatigue appearing after the 6MWT. One study in patients with sarcoidosis [9] measured the quadriceps muscle torque after the 6MWT, showing a reduced peak torque in 27% of patients. Other studies in ambulatory participants with spinal muscular atrophy [12–14] also measured the peak torque of the knee flexor and hip abductor muscles and used surface electromyography from four muscle groups, including the foot muscles (rectus femoris, biceps femoris, gastrocnemius, and tibialis anterior). No previous study had combined the measurement of the peak force produced by the ankle plantar flexor muscles and a pedobarographic evaluation after the 6MWT. As cited above, an instability of the foot characterized by enhanced CoP deviations was already reported after fatiguing tasks including intensive athletic or military marching [17], high-heeled gait [18], running at elevated speed on a treadmill [15], and sustained static contractions of the foot muscles [16]. In the present study, the modest (but significant) post-6MWT decrease in the ankle plantar flexion forces did not allow to assess the existence of a post-6MWT fatigue of the leg muscles. Muscle fatigue could be only suspected taking into consideration the accentuation of the posture sways always present after the 6MWT.

However, it is worth underlining that we did not measure any significant intergroup differences in the magnitude of both the reduced ankle plantar flexion force and the posture changes

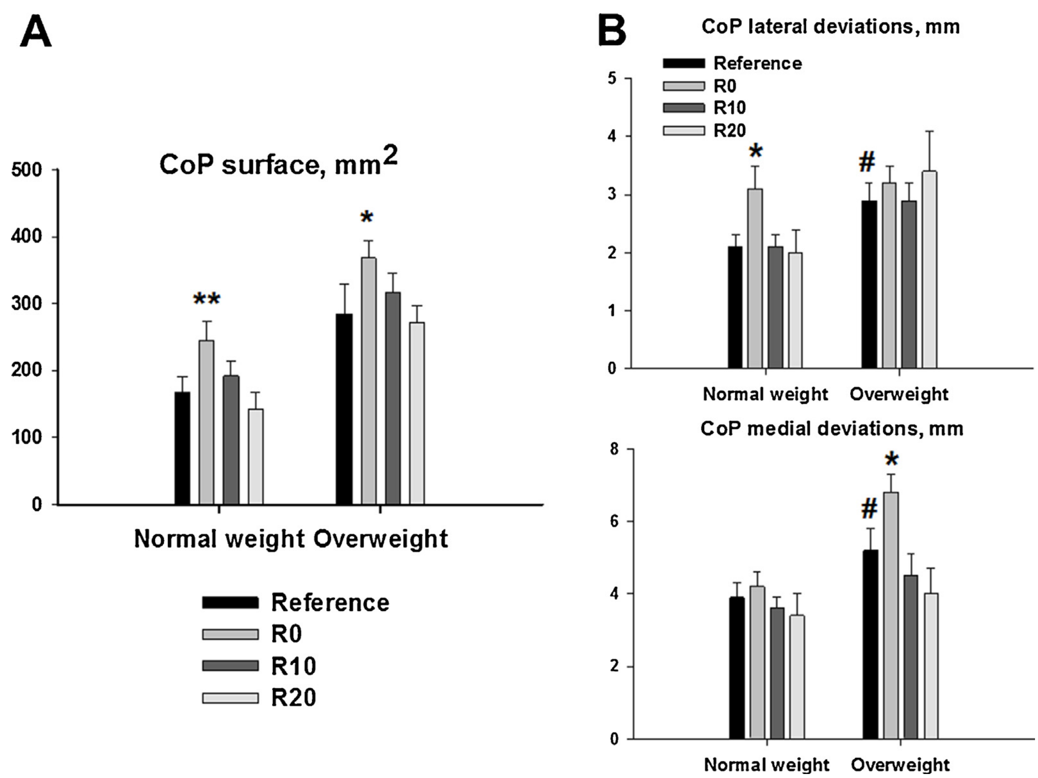

Fig. 3. The 6MWT induced posture changes. The center of pressure (CoP) surface increased (A) and CoP deviations also occurred (B). After the 6MWT, increased lateral CoP deviations were measured in subjects with normal weight while medial CoP deviations occurred in overweight individuals. Asterisks denote significant 6MWT-induced changes in the reference values measured before the 6MWT ($^{*}p < 0.05$; $^{**}p < 0.01$). Symbol # denotes significant intergroup difference between reference values ($^{\#}p < 0.05$).

(increased mean plantar contact area and CoP surface) after the 6MWT despite overweight being a factor that might increase muscle fatigue during walking. Thus, we suggest that the post-6MWT changes in muscle force and posture could not result from a fatigue of the leg muscles but perhaps from an alteration of the motor control. The sensory pathways carried by the muscle spindles afferents play a key role in both the development of the muscle force and the control of the posture sway [29]. We already reported a reduction of the myotatic reflex after a static foot inversion [16] or a static handgrip [30] and a recent study [31] also reported that the sole passive stretch of human plantar flexors inhibited the motoneuron facilitation through the myotatic reflex. It is well known that lactic acid released by the working muscle at a high strength markedly depresses the activation of the muscle spindles [32,33] but it seems doubtful that a muscle acidosis may occur during the 6MWT. Thixotropy, i.e. the changes in mechanical properties of extra- and intrafusal myofibrils induced by brief contractions or passive extensions, might explain the reduced myotatic reflex [34] independently from any contractile fatigue of the leg muscles. Thus, both the changes in the ankle plantar flexion forces and posture here reported after the 6MWT could simply result from the thixotropic mechanism.

4.4. Conclusions

After a 6MWT, we reported in both overweight and normal weight healthy subjects that even a moderate activity such as the 6 min test was shown to change some variables associated with foot function. These appear to relate to a change in muscle function in patients with already compromised muscle function, such as older people, though with history of falls, and the chronic hypoxemic patients where muscle disuse markedly potentiates the alteration of the sensorimotor control [35].

Conflict of interest statement: All authors disclose any financial and personal relationships with other people or organizations that could inappropriately influence (bias) their work.

Author contributions: Each author has contributed to writing the paper, to the conception and design of the experiments, collection, analysis and interpretation of data, and drafting the article. All authors approved the final version of the manuscript and all persons designated as authors qualify for authorship, and all those who qualify for authorship are listed.

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