JAPMA Online Early **DOI: 10.7547/18-093**

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ORIGINAL ARTICLE

Effects of Orthotic Insoles on Gait Kinematics and Low Back Pain in Subjects with Mild Leg Length Discrepancy

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Background: Mild leg length discrepancy (LLD) increases the biomechanical asymmetry during gait, which leads to low back pain (LBP). Orthotic insoles (OI) with a directly integrated heel lift were used to reduce this asymmetry and thus the associated LBP. The aim of this study was to analyze the biomechanical adaptations of the locomotor apparatus during gait and the subjective pain ratings before and after the establishment of OI use.

Methods: Eight subjects with mild LLD (≤ 2.0 cm) underwent 3-dimensional biomechanical analysis while walking, before and after 3 weeks of OI use. LBP was assessed separately before both measurement sessions using a visual analogue scale.

Results: The analysis of the kinematic parameters highlighted individual adaptations. The symmetry index (SI) of Robinson indicated that OI had no significant effect on the kinematic gait parameters and an unpredictable effect across subjects. OI use significantly and systematically (in all subjects) reduced LBP ($P < 0.05$), which was correlated with changes in ankle kinematics ($P = 0.02$, r = 0.80).

Conclusions: The effects of OI on gait symmetry are unpredictable and specific to each subject's individual manner of biomechanical compensation. The reduction in LBP seems associated with the improved ankle kinematics during gait.

Keywords: Leg length inequality, asymmetry, locomotion, kinematics parameters, chronic lumbar pain.

Leg length discrepancy (LLD) affects between 40 and 70% of the population [1,2]. LLD is due to anatomical deformities originating from true bony leg length differences or a functional deformity originating from abnormal lower limb movements [3]. LLD can thus be divided into two etiological groups: anatomical and functional. Anatomical LLD can be defined as those discrepancies associated with a shortening of bony structures, and it can further be subdivided in two subgroups: congenital and acquired. The congenital conditions include mild developmental abnormalities found at birth or childhood and/or abnormal developmental disorders. Acquired conditions include trauma, fractures, orthopedic degenerative diseases and surgical disorders. Functional LLD is an asymmetrical leg length that does not result from a true bony length difference. Instead, it results from an alteration in lower limb mechanics, such as joint contracture, static or dynamic mechanical axis malalignment, muscle weakness or shortening [1,4]. Whatever the etiology of the LLD (*i.e.*, anatomical or functional), Moseley [5] suggested classifying the discrepancy into three severity grades: mild (0.0-2.0 cm), moderate (2.0-6.0 cm), and severe (6.0-20.0 cm). Other authors suggested a different classification: mild (0.0-3.0 cm), moderate (3.0-6.0 cm), and severe (> 6.0 cm) [1,6–9]. Furthermore, Walsh et al. [10] considered a subject with LLD less than 0.5 cm to be normal. Therefore, the cut-off point to classify mild and moderate LLD is not completely consensual. Although Moseley [5] suggested that mild LLD requires no treatment, Reid and Smith [9] recommended either no treatment or OI. This divergence in the cut-off point and the recommended treatment is likely explained by the lack of consensus in the literature regarding the biomechanical effects of mild LLD during gait [11–15].

The symmetry index (SI) of Robinson [16] is able to quantify the gait asymmetry [17,18]. It evaluates the gait pattern in patients with LLD and estimates the acceptable range of discrepancy before and after a heel lift or an OI is worn. In the study of Liu et al. [18], patients with a mean inequality of 0.5 cm showed a smaller SI value than those in a group with a mean inequality of 1.4 cm. A mean inequality of 2.3 cm was found to be an acceptable SI [18]. Yet in a more recent study, subjects with LLD between 1.0 and 2.3 cm exhibited significantly less symmetrical gait [17]. Indeed, Seeley et al. [17] evaluated the effect of LLD on gait asymmetry in 26 subjects. Nineteen subjects exhibited < 1.0 cm of LLD with an average of 0.4 cm (SD 0.3) and 7 subjects exhibited a relatively large LLD (≥ 1.0 cm) with an average of 1.7 cm (SD 0.4). This study, which used a symmetry coefficient, revealed that LLD was not significantly related to the degree of bilateral symmetry for joint angles during gait. This result nevertheless supported the idea that LLD influences gait symmetry for joint moment and power at the hip, knee, and ankle joints. For all the subjects, statistically significant relationships were observed between mild LLD and gait asymmetry, with higher values of asymmetry for subjects with ≥ 1.0 cm of LLD.

Murray and Azari [19] and Tallroth et al. [20] provided support for the prevailing theory that even mild LLD (≤ 2.0 cm) can cause excessive mechanical pressure, with consequences in terms of excessive and abnormal loading of the lower extremities and the lumbar spinal joints. Knutson et al. [21] and Guichet et al. [22] assumed that LLD is a symptomatic alteration if the discrepancy is greater than 2.0 cm. However, White et al. [23] recommended equalization of all discrepancies < 3.0 cm. Walsh et al. [10] evaluated the effect of 1.0- to 5.0-cm foot lifts on the lower limb kinematics of seven normal subjects with no significant LLD (*i.e.*, not greater than 0.5 cm). They demonstrated that compensation started at 1.0 cm for all levels of the locomotor apparatus, leading to asymmetrical gait. LLD affects the kinematics and kinetics of gait [11]. Indeed, it was found to modify the biomechanical amplitudes of the locomotor apparatus in such a way as to compensate the short limb [11].

However, LLD generates biomechanical disturbances like pelvic obliquity, spinal curvature and asymmetry in the lower extremity joints and pelvis [16–18,24], and this in turn favors the occurrence of hip osteoarthritis, postural imbalances and LBP [1,4,25]. In the study of Young et al. [26], a lift greater than 1.5 cm was placed under the foot and caused a lateral pelvic tilt of 1.2°. Moreover, Needham et al. [27] demonstrated that the difference in the range of motion (RoM) of the pelvis and lumbar spine was minimal between barefoot and mild LLD conditions. Three LLD conditions (1.0, 2.0, and 3.0 cm) were simulated using modified pieces of high-density EVA attached to the right foot (for LLD condition = 1.0 cm, pelvic range of motion adaptation: sagittal plane 0.04°, frontal plane 0.3°, transverse plane 0.7°; LLD condition = 2.0 cm, sagittal plane 0.2°, frontal plane 1.4°, transverse plane 0.6°). Subjects with LLD of 0.6 cm presented LBP because they had made abnormal spinal adaptations (scoliosis or hypo-hyperlordosis) in static and dynamic positions [28–30]. Indeed, in the frontal plane, LLD leads to a lateral pelvic tilt on the shorter side as well as pelvic torsion in the sagittal plane. These pelvic positions cause a body shift to the shorter side and scoliotic attitudes. LLD also causes a slight curvature of the spine when the pelvic girdle tilts laterally in the frontal plane [31]. These adaptations of the anatomical position may result in the onset of LBP [28]. The minimal LLD necessary to cause LBP has been a matter of debate. Most researchers [1,32] agree that LLD of more than 2.0 to 3.0 cm can cause LBP. However, they disagree on the effect of an LLD of less than 1.0 cm. Some have stated that an LLD of 0.9 cm changes the angle of the lumbar facet joints. An LLD as small as 3.0 cm was found to induce postural changes [28,33–35]. Mild LLD may cause various biomechanical adaptations that can lead to LBP.

It appears clearly that mild LLD causes asymmetry in the lower extremity joints and pelvis, leading to stress and strain with a disturbance in normal biomechanical function. The functional

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alterations increase the biomechanical disorders, the asymmetrical gait, and LBP, and may favor the development of hip osteoarthritis and stress fracture. OI is a treatment often used in podiatry that might reduce the biomechanical asymmetries [18,36] and therefore LBP [36,37]. Moreover, Defrin et al. [28] and Golightly et al. [38] have shown that OI may reduce physical disability and the intensity of LBP in subjects with LLD ≤ 1.0 cm. The objective of this observational study in a podiatry center was to examine the effects of OI on gait kinematics and low back pain in subjects with mild leg length discrepancy. To carry out this study, we followed the methodology used in this podiatry center. We hypothesized that the asymmetries of the locomotor apparatus would be rebalanced after OI use, which would reduce LBP.

METHODS

Subjects

Eight subjects (5 men; 3 women; age = 28.3 years (SD 8.2); body mass index = 23.8 $kg.m^{-2}$ (SD 1.7); height = 1.74 m (SD 0.09)) volunteered to take part in this study and were recruited in a podiatry center (PP n°IRB00012476-2020-15-07-61). The ages ranged from 20 to 45 years (*i.e.*, bone growth had ended and bone degeneration was limited). All had been diagnosed with mild LLD ≤ 2.0 cm by a pedicurist-chiropodist using a clinical procedure, with the minimal LLD inclusion criterion being 0.5 cm [10] (mean LLD = 1.0 cm; standard deviation = 0.2 cm). The reason for the chiropodist consultation was chronic LBP, with all subjects reporting back pain for 3 months or more (the time of onset of chronic status) [39]. Other causes of the LBP were considered during the clinical examination, with the pedicurist-chiropodist inquiring into the

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medical antecedents before determining whether the LLD should be corrected. The inclusion criteria were no history of surgery, no history of lower limb injury, and no neuromuscular or cardiovascular pathology related to the LLD in the last 6 months. Subjects who needed outside help to walk could not participate in the study. This research used an observational study protocol to follow the standard course of care in a podiatry center. The care included the chiropodist's clinical examination to determine the degree of LLD and treatment (OI), with the addition of biomechanical analysis (motion capture) of walking to observe the effects of the OI on the LLD. The entire study was framed by healthcare professionals in a health center. Before the study, all subjects received both verbal and written explanations about the study procedure. The study was conducted according to the Declaration of Helsinki and French national regulations (Decree n°2017-884 of 9 May 2017).

Procedure

A clinical examination was performed before the initial session (S_1). A professional in podiatry with 25 years of clinical experience verified the presence or absence of mild LLD using the direct method (the tape measurement method) with the subject in supine position, as described in the literature [1,2,4,40]. The subjects wore clothing that allowed for palpation and tape measurement with minimal hindrance, while their modesty and comfort were maintained. They were placed on a treatment table with their pelvis in relaxed and neutral alignment [40–43]. The LLD of all subjects was assessed by the same pedicurist-chiropodist using the same tape measure to measure the distance between two anatomical points: measurement from the anterior superior iliac spine (ASIS) to the distal tip of the medial malleolus [40]. The mean of three readings was used for analysis because the reliability of these measurements was enhanced by use of mean values [41]. This direct method has concurrent validity with radiographic measurement, with a Pearson product moment correlation of 0.98 and inter-tester reliability (ICC) of 0.99 [44]. For this study, we evaluated the intra-tester reliability for tape measurement with an ICC of 0.85. The mean value of LLD was 1.0 cm (SD 0.2).

For S_1: gait kinematic analysis was performed with the Vicon™ system (Vicon Oxford Metrics, Oxford, UK) to establish the biomechanical reference values [45]. The Vicon™ system consists of 12 infrared video cameras set at a frequency of 120 Hz. Marker placement corresponded to the Plug-in Gait lower body model (Figure. 1) [46] with 16 reflecting passive markers placed on the skin to determine the lower limb coordinates. The markers were carefully attached by the pedicurist-chiropodist, who had 25 years of clinical experience. Marker-attaching was repeated several times to ensure optimal repeatability and exact positioning of the markers from session to session [46]. The subjects wore their own standard, commercially available shoes for this study, which was necessary because the aim was to decrease their daily pain. After 10 minutes of familiarization with the environment, four acquisitions over 15 meters of spontaneous walking were made to obtain five gait cycles per acquisition for a total of 20 cycles per subject (the 3-4 first and last strikes of each acquisition were not considered in the data processing because the start and stop were located 3 meters from the recording space).

During S_1, LBP was estimated using a visual analogue scale (VAS) graded centimeter by centimeter from 0 (absence of pain) to 10 (maximal pain). The VAS provides a subjective assessment of pain severity [47]. The assessment was made 30 minutes after kinematic analysis. The instructions to the subjects were to answer in a spontaneous and sincere way.

Customized bilateral OI were made for each subject by the pedicurist-chiropodist based on the first 3D gait analysis and the clinical examination. The technique was thermoforming: the OI were first warmed before being molded under a pillow mold to obtain the footprint in the anatomical position (Figure 2A). The components were ethinyl vinyl acetate, resin, and polyethylene and different pads were used (high density, low elasticity) for comfort, absorption and correction (Figure 2B). Once the OI were molded, they were further directly shaped to effectively counteract the effects of LLD and help the subjects achieve rebalance in the kinematics of walking (Figure 2C). They were made according to the therapeutic needs of the subjects, with a heel lift incorporated into the OI of the short leg. The heel lifts were partially corrective of the LLD, to 50%, and were shaped from the calcaneus to the Chopart joint. This corrective strategy is used empirically by the pedicurist-chiropodist. At the end of the process, the pedicurist-chiropodist checked the impact of the OI by examining the iliac crest position in the frontal plane while the subject was standing.

Between S_1 and S_2, the subjects were asked to carry on their everyday activities for 3 weeks while wearing their custom OI, as this was the standard care path of the podiatry center.

For S_2, kinematic and subjective analyses were repeated with the same shoes as in S_1, but after the subjects had been wearing their OI for the 3 weeks.

Data reduction

The kinematic parameters were assessed using Polygon software (Vicon Oxford Metrics, Oxford, UK). The gait kinematics included: 1) hip flexion-extension and adduction-abduction and the rotations (the joint angle between the longitudinal axis of two adjacent segments) represented by the motion of the thigh relative to the pelvis; 2) pelvic obliquity, tilt and rotations (the angle between a segment and the right horizontal of the distal extremity) between the pelvis and the laboratory coordinate system; 3) knee flexion-extension represented by the motion of the shank relative to the thigh; and 4) rearfoot dorsiflexion-plantarflexion between the shank end and the foot [11]. With the Plug-in Gait lower body model (Figure 1), only two markers were used on the foot to define the measurement of ankle joint motion to flexion-extension. Further, given the finite accuracy and resolution of the motion analysis system, the estimates of inversion-eversion may not have been sufficiently accurate to be of any practical use [45].

Data analysis

For the kinematic values, maximum and minimum peaks were assessed to identify the joint amplitudes. Then the average of the amplitudes (for the hip, knee, ankle and pelvis) was calculated on the set of the walking cycles of each subject (n = 20 cycles, Table 1). Furthermore,

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to assess the difference in joint amplitude between the lower limbs, we determined the SI of Robinson (Equation 1) [16], according to the following formula:

SI = 1-((value RJ – value LJ) ÷ (0.5 × (value RJ + value LJ))) × 100

(Eq. 1)

RJ corresponds to the right joint, and LJ to the left joint. The SI supplies a percentage, which in the case of perfect symmetry gives a 100% value.

Statistical analysis

Analysis was performed using SPSS software version 20 (Armonk, NY: IBM Corp, US). The kinematic parameters and pain scores were tested for normal distribution using the Shapiro-Wilk test, then compared using the paired Student's t-test (for normally distributed scores) or the Wilcoxon signed-rank test (for non-normally distributed scores).

The relationship between the changes in pain and the kinematic changes was examined with the Bravais-Pearson parametric correlation test or the Spearman non-parametric test, according to the distribution normality. The significance was set at $P = 0.05$.

RESULTS

Comparisons of the RoM between the short limb and long limb in Table 1 showed no significant change ($P > 0.05$). However, a complementary visual analysis of the individual results revealed considerable diversity in the kinematic evolution, underscoring the highly individual biomechanical adaptations to the OI with 50% partial correction of the LLD.

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Range of motion

No significant difference in the asymmetry of joint RoM was noted between the pre- and post-assessments ($P > 0.05$). The intra-individual difference *(RoM right leg – RoM left leg (before))/ (RoM right leg – RoM left leg (after))* showed a non-significant decrease in joint asymmetry in Table 1. The bold values denote a reduction of asymmetry, meaning a symmetry improvement. These values highlight a decrease in the difference of RoM with the use of OI.

Symmetry index of Robinson

Compared with the initial SI results, the use of OI resulted in no significant change in any parameter observed in this study, as shown in Table 2.

Visual analogue scale

The comparison of the VAS scores between S_1 and S_2 revealed that all subjects reported less pain after 3 weeks of wearing the 50% partially corrective OI (Figure 3).

Correlation analysis revealed that only the improvement in ankle symmetry was significantly correlated with the decrease in LBP ($P = 0.02$; $r = 0.802$).

DISCUSSION

The objective of this observational study was to analyze the effects of OI on the parameters of gait kinematics in subjects with mild LLD (≤ 2.0 cm), associated with changes in LBP. The case series evaluated the effect of wearing OI for 3 weeks (partially corrective: 50% of LLD) on the

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biomechanics of walking and the LBP of subjects with mild LLD. The results did not show a significant decrease in the gait asymmetry. However, this study highlighted a significant decrease in LBP for all subjects after 3 weeks of wearing OI.

LLD has been recognized as a source of musculoskeletal problems for decades [1,4,28,42,48], yet it is a controversial issue among researchers and clinicians. Although its existence is obviously not in doubt, there is no consensus regarding the biomechanical effects of mild LLD during gait [11–15]. However, numerous authors [10,11,17,19,20,34] consider mild LLD as being at the origin of biomechanical disorders of the lower limbs.

Podiatrists generally consider OI as a means to regulate the biomechanical compensations spontaneously made by subjects with LLD [36]. To detect the LLD, the pedicurist-chiropodist used the direct method with a tape measure. This method measures the distance between two anatomical points while the subject is lying in a supine position [1,2,4,40]. Although imaging techniques are considered to be the most accurate method for determining LLD, they are costly, time-consuming, and, in the case of radiographs and CT, the patient is exposed to radiation. As a result, alternative clinical methods have been developed [1]. There are still differences of opinion in the literature as to the reliability and validity of this method. The debate can be attributed to several potential sources of error, such as the difficulty of palpating bony landmarks, anatomical bony asymmetry, bony anomalies of the ASIS and malleoli, excess adipose tissue due to weight gain, differences in leg circumference and angular deformities [4,49]. However, we did not have access to radiographic or scanographic techniques to measure the LLD for this study. According to Neelly et al., when clinicians need to accurately and reliably measure LLD, the use of the tape measure is appropriate [43]. Subjects with mild LLD make individual biomechanical compensations that can increase the biomechanical gait asymmetry [17]. The eight subjects of this study presented mild LLD ($\leq$ 2.0 cm) and the SI indicated that OI with a partial correction of 50% of the LLD had no significant effect on the kinematic parameters. The intra-individual differences in Table 1 revealed the individual character of the biomechanical adaptations [4]. For example, in subject 1, the results revealed that the joint symmetry was improved for the set of the variables of pelvic obliquity (S_1 = 1.4°; S_2 = 0.2°), pelvic tilt (S_1 = 1.3°; S_2 = 0.1°), pelvic rotation (S_1 = 0.3°; S_2= 0.2°), rearfoot (S_1= 3.6°; S_2 = 0.6°), hip adduction (S_1 = 2.6°; S_2 = 0.6°) and hip rotation (S_1 = 31.1°; S_2 = 26.4°). On the other hand, subject 4 showed improvement only for the variables of hip rotation and pelvic rotation.

In fact, the striking phenomenon was the unpredictable and highly specific effects of OI on gait symmetry and the individual biomechanical compensations developed by the subjects.

According to our results in Table 1, OI use improved joint symmetry for hip (sagittal, frontal, transversal) in five subjects and for knee flexion-extension in three subjects. For the rearfoot, OI decreased the asymmetry in three subjects. For the pelvis, reductions in the asymmetry were observed for four subjects in the three planes. However, as seen from Table 1, we can see that all the improvements do not always concern the same subjects. The findings overall agreed with those of Liu et al. [18] and Seeley et al. [17], who demonstrated that the use of OI for subjects with mild LLD had no significant effect on joint symmetry, although they observed a trend toward specific improvements.

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Several factors can explain the lack of improvement in some of the kinematic parameters. For example, OI use increased the joint asymmetry in certain subjects. For subject 4, OI increased the joint asymmetry except for hip rotation and pelvic rotation, as seen in Table 1. It may be that the subjects had to reorganize their biomechanical solutions to LLD in order to adapt to the modifications brought by the OI. Indeed, the postural adjustments with mild LLD are numerous. For example, according to Resende et al. [11] and Defrin et al. [28], for pelvic obliquity, the iliac crest is low on the side of the short limb and high on the side of the long limb, which may help to explain the relationship between mild LLD and lower limb and lower back injuries. Resende et al.[11] and Khamis et al. [15] have shown that, during the swing phase, significantly greater knee and hip flexions were observed on the longer side. Moreover, for Blake and Ferguson [32], ankle pronation functionally decreases the length of the longer leg. And these postural adjustments are very much specific to each subject [50,51]. It is also likely that 3 weeks between the analyses was not sufficient to allow for a regulation of the compensatory system in all the subjects, which would have improved joint symmetry. However, the literature provides no precise indication on the time needed for compensatory system regulation after correction. We therefore chose 3 weeks, as this was the standard care path of the podiatry center. We thus assume that OI may have disturbed the individual compensatory systems, *i.e.*, the postural mechanism that each individual had devised to counteract the effects of LLD. Indeed, Cooperstein and Lew [35] and Defrin et al. [28] have discussed this compensatory system before OI correction and the time for adaptation after OI use that may be needed before improvements are seen. For this pilot study, we followed the standard protocol of the

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center's pedicurist-chiropodist, with a heel lift in the OI to attenuate the biomechanical disorders of LLD. Indeed, the usual conservative correction of LLD is to apply a heel lift to the shorter leg. When a heel lift was applied to patients with an LLD of more than 10 mm, it reduced their LBP and increased the ROM of the lumbar spine [28,33,52,53]. In addition, using orthotics for LLD can improve gait symmetry [28,37,54]. However, Khamis et al. [4] noted that a heel lift does not affect the entire stance phase of the gait cycle because during the terminal stance after the heel rise, weight-bearing is solely on the forefoot. The induced lift will therefore be ineffective at that particular instance of gait. The corrective value of the OI (50% of the LLD) used in this study may not be optimal. However, according to Campbell et al. [7], little consensus has emerged regarding the correction strategy value. There are several strategies for correcting LLD, but in many studies they have been inadequately described.

The precise incidence and prevalence of LBP are difficult to characterize due to the significant heterogeneity in the epidemiologic studies [55,56]. The exact mechanism by which LLD causes or augments LBP is not clear. It has been suggested that LLD causes asymmetry in the lower limb joints, spine and pelvis, leading to stress and strain with a derangement of normal biomechanical function and functional alterations. Several authors have underlined the close relationship between LLD and LBP [1,4,15,28,36,55]. Moreover, the patients of the center were referred by their doctor for LBP linked to untreated LLD. Our results showed a significant and systematic decrease in LBP for all subjects after 3 weeks of wearing a partially corrective OI (50% of the LLD). Furthermore, this essential finding seemed particularly associated with the kinematic change at the ankle (sagittal plane). In the present study, only the improvement in ankle symmetry was significantly correlated with the decrease in LBP (*P* = 0.02; r = 0.802). Indeed, the study of Menz et al. [57] found that pronated foot function may contribute to LBP. Moreover, according to Blake and Ferguson [32], in subjects with LLD, a significant difference between the legs regarding the position of the calcaneus can be observed during gait. This corresponds to a mechanism of shortening or compensatory extension of the lower limbs, by the eversion or inversion of the foot. In our study, OI may have had an effect on the calcaneus by modifying its position. Thereby, OI may have played a role in decreasing pain. However, for the ankle kinematic parameters in the frontal plane, we used the Plug-in Gait lower body model by modeling the foot as a single rigid segment [45]. As noted by Dixon et al. and Leardini et al. [58,59], the foot and ankle complex is an intricate structure made up of several independent segments. Thus, single-segment foot models are insufficient to reveal intra- and inter-segment foot kinematic changes during gait and calculate ankle pronation (frontal plane). In a future study, we will integrate a multi-segment foot model, such as the Oxford Foot Model (OFM) [58], in order to better understand the pronation effect on LBP in subjects with LLD.

The second factor that might explain the decrease in LBP was the change in pelvic kinematic parameters. To preserve skeletal integrity, muscles will compensate for shortcomings in ways that may cause LBP [28]. A good example is the psoas muscle, which attaches at the lumbar vertebrae and ensures the structural stability of the vertebral column, sometimes entailing LBP [33]. LBP is one of the main reasons for consultation in podiatry by people with LLD $\leq$ 1.0 cm.

Indeed, the changes in the kinematic parameters were non-significant despite a tendency toward improved symmetry in some of the joint amplitudes, such as the strong improvement in pelvic obliquity (S_1 = 85.1%; S_2 = 91.7%) and pelvic rotation (S_1 = 92.8%; S_2 = 95.1%). According to Rhodes and Bishop [60], LLD can generate pelvic twisting, which can lead to LBP. The biomechanical solution often used to compensate the LLD is a lateral tilt of the pelvis and lumbar spine, which causes asymmetrical weight-bearing and chronic functional changes in these joints and the lower limb joints [36]. The study of Betsch et al. [61] showed that the correlation between mild LLD and pelvis tilt or pelvic twisting is significant. Indeed, in our study, minimal and non-significant differences were observed for the pelvis in the frontal plan with an average difference in RoM of 1.0°. This confirms the study of Needham et al. [27], who reported a RoM difference in pelvic obliquity of 1.4°. Differences in RoM and patterns of movement for the pelvis were minimal in LLD conditions. These observations can be attributed to the various kinematic compensatory strategies of the lower limbs, which would require more in-depth investigation.

The biomechanical compensatory strategies related to LLD are complex and they were not completely corrected in this study, despite significantly reduced LBP. Our study confirmed the view of White et al. [23] that equalizing leg lengths should be considered even with bilateral differences < 3.0 cm. Indeed, the slightest disparity should not be neglected because of the biomechanical changes individuals make to compensate for the LLD effects [11]. These effects can lead to chronic pathologies like knee and hip degenerative osteoarthritis in the short limb.

At the spine, disc herniation, functional scoliosis and LBP due to unilateral pelvic tilt are observed. These biomechanical changes can cause an overload during walking and increase the risk of injury [11,62].

Although the sample was limited, our results suggest new research perspectives. The OI with a partial corrective of 50% of the LLD might have an influence on other parameters that were not investigated in this study. Perttunen et al. and Gurney et al. [63,64] suggested that LLD has an influence on kinetic, muscular, neurological and tendinous parameters, as well as static posture. These factors might explain the significant decrease in the sensation of pain. Perttunen et al. [63] noted that electromyographic and neuromuscular measurements have rarely been used to observe the effects of LLD on the degree of asymmetry. Another methodology for OI design might have been considered. For example, a sole lift placed along the entire foot, from heel to toe, would have simulated an effect throughout the gait cycle. Another corrective value of the LLD might also have been considered. Complementary examinations with a larger sample should be considered in future studies to better monitor all the mechanisms of LLD during gait, with one example being the creation of a database with all the parameters of gait biomechanics and a comparative study between the OI, the heel lift and the sole lift placed along the entire foot. It might be interesting to consider all the movements in the lower limbs such as the knee and ankle rotations in the transverse plane. For the kinematic analysis, we intend to integrate a multi-segment foot model such as the Oxford Foot Model (OFM) [58]. Last, we were wary of the potential bias that comes with subjective reporting of VAS, yet is should be noted that the subjects were aware that the treatment was meant to decrease their LBP. Future trials should be blinded to reduce bias, in order to obscure the real effect of the orthopedic treatment of LBP.

CONCLUSIONS

After subjects with mild LLD of ≤ 2.0 cm wore OI for 3 weeks, we observed unpredictable and very individual changes in the symmetry of the joint amplitudes but significant decreases in LBP. This reduction in pain seemed associated with an improvement in the ankle kinematics during gait. It therefore seems reasonable to treat mild LLD with OI, which can reduce the postural imbalances that occur with LLD and improve well-being. OI are a noninvasive and inexpensive therapeutic means that can be added to the treatment of mild LLD. Optoelectronic systems (3D analyses) provide quantitative data in dynamic situations.

Financial Disclosure: None reported.

Conflict of Interest: None reported.

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JAPMA Online Early **DOI: 10.7547/18-093**

This Original Article has been reviewed, accepted for publication, and approved by the author. It has not been copyedited, proofread, or typeset and is not a final version.

Table 1: Differences in range of motion between the right leg and left leg during pre-and post-OI (S_1 / S_2).

Measure (°)	Hip flex/ext		Hip add/abd		Hip rotation		Knee flex/ext		Rearfoot dorsi/plantar		Pelvic obliquity		Pelvic tilt		Pelvic rotation	
	S_1	S_2	S_1	S_2	S_1	S_2	S_1	S_2	S_1	S_2	S_1	S_2	S_1	S_2	S_1	S_2
Subject 1	3.9	8.7	2.6	**0.6**	31.1	**26.4**	1.4	6.7	3.6	**1.6**	1.4	**0.2**	1.3	**0.1**	0.6	**0.2**
Subject 2	0.7	2.5	1.3	**0.7**	9.9	**9.3**	1.6	7.3	2.5	**1.6**	0.4	**0.1**	0.2	0.3	0.4	**0.1**
Subject 3	4.5	**3.2**	2.6	**2.0**	21.0	29.5	7.3	**5.1**	3.1	3.4	4.5	**0.7**	2.0	**0.1**	0.1	0.2
Subject 4	2.2	9.7	0.3	0.5	24.7	**15.8**	1.9	11.6	1.5	3.2	0.9	1.1	0.1	0.1	4.5	**0.0**
Subject 5	0.9	**0.6**	2.2	3.1	21.5	24.6	4.8	**1.6**	1.3	7.6	0.3	0.3	0.7	**0.0**	0.3	1.1
Subject 6	5.2	**2.7**	0.2	1.2	6.7	**0.1**	3.2	**1.1**	1.8	5.6	0.1	1.2	0.9	1.1	0.4	0.9
Subject 7	0.8	**0.2**	2.1	**1.0**	19.5	**5.0**	0.8	7.6	5.8	**0.7**	0.3	0.4	0.5	**0.2**	0.0	0.6
Subject 8	4.4	**3.8**	1.2	**0.8**	9.6	15.2	0.8	2.0	3.5	4.3	0.5	**0.3**	0.1	0.2	0.2	**0.1**
Mean	2.8	3.9	1.6	**1.2**	18.0	**15.7**	2.7	5.4	2.9	3.5	1.0	**0.5**	0.7	**0.3**	0.8	**0.4**
SD	1.9	3.5	1.0	0.9	8.5	10.6	2.3	3.7	1.5	2.3	1.5	0.4	0.7	0.4	1.5	0.4

S_1 = initial session/ S_2 = final session/ SD = standard deviation / The values in bold denote a reduction in asymmetry.

Table 2: Values of the symmetry index of Robinson (%) for the initial session and final session

Measure	**SI (%)**				**Sign.**
	S_1	**SD**	**S_2**	**SD**	
Pelvic obliquity	85.1	21.7	**91.7**	7.1	$P = 0.41$
Pelvic rotation	92.8	4.9	**95.1**	4.2	$P = 0.88$
Pelvic tilt	81.3	15.7	**91.5**	12.3	$P = 0.13$
Hip flex/ext	93.6	4.6	90.1	9.1	$P = 0.38$
Hip abd/add	86.7	8.2	**89.4**	6.3	$P = 0.39$
Hip rotation	30.7	25.0	**39.7**	35.0	$P = 0.21$
Knee flex/ext	95.8	3.5	91.1	6.7	$P = 0.16$
Rearfoot	90.3	5.2	89.1	6.9	$P = 0.77$

SI = symmetry index of Robinson/ SD = standard deviation / Sign. = significant / S_1 = initial session / S_2 = final session / The values in bold = positive changes.

 DOI: 10.7547/18-093

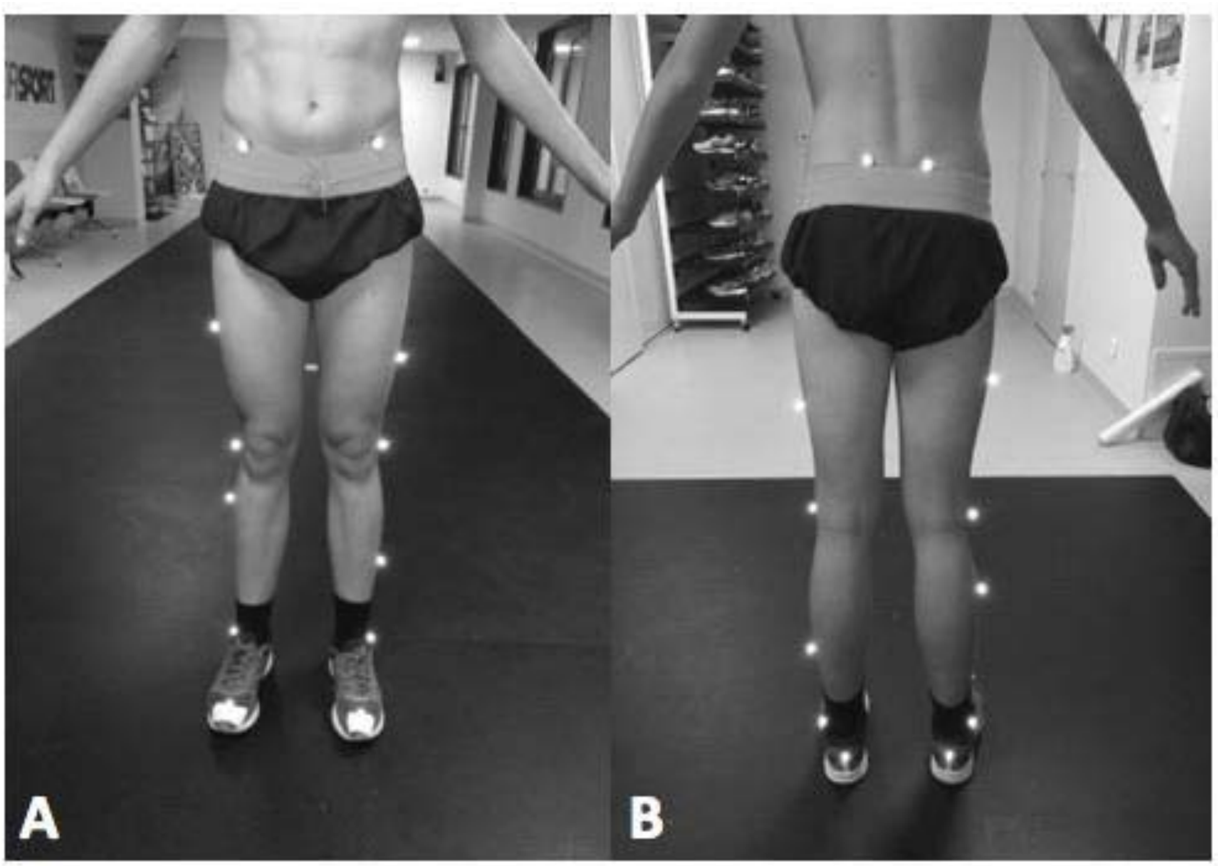

Figure 1: Marker placement – anterior (A) and posterior (B) views

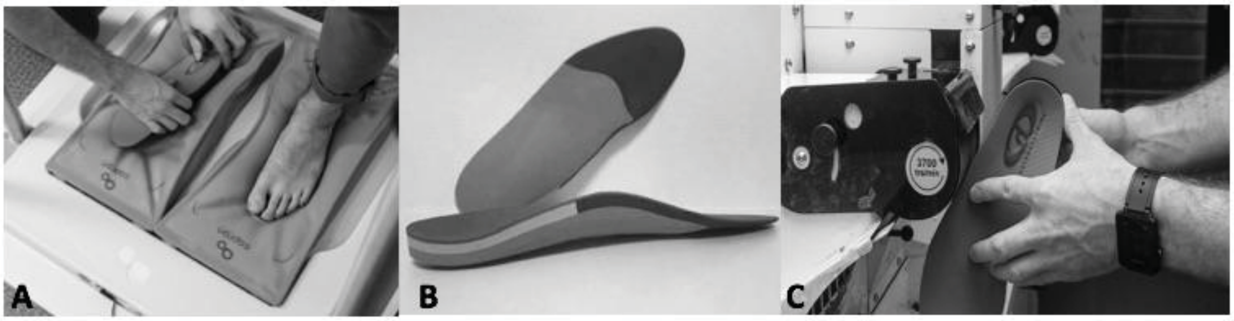

Figure 2: Thermoforming the orthotic insoles (A); Orthotic insoles in ethinyl vinyl acetate, resin, and polyethylene (B); Further shaping the orthotic insoles (C)

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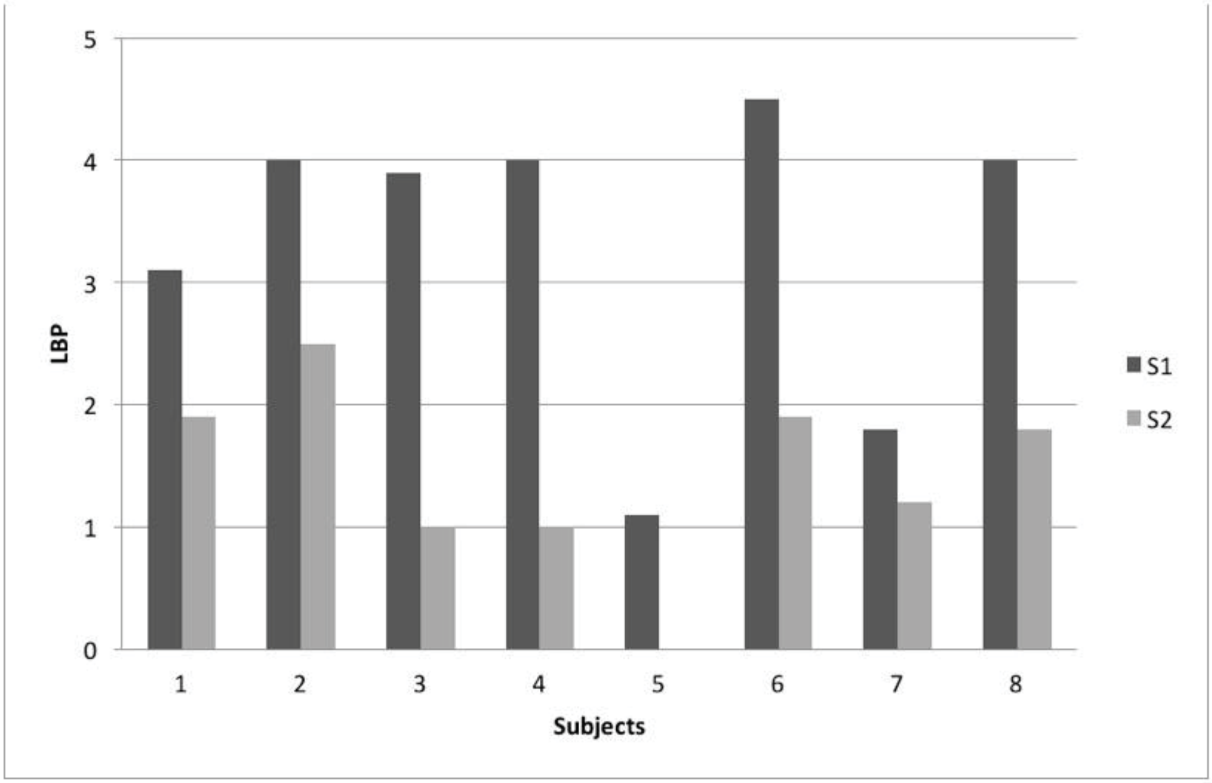

Figure 3: Low back pain (LBP) evolution (S_1 = initial session / S_2 = final session / * *P* <0.05) /

Subject 5 S_2 had zero pain