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The effects of real and artificial Leg Length Discrepancy on mechanical work and energy cost during the gait

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ABSTRACT

Background: The impacts of Leg Length Discrepancy (LLD) on the kinematic and dynamic parameters of walking have been widely discussed. But little is known on total mechanical work and energy cost. These two variables are more representative of the functional impairment undergone by the LLD patients.
Aim: To assess the changes of the mechanical work and energy cost of walking in subjects with real LLD and to compare their results with healthy subjects in whom the LLD has been simulated.
Method: The mechanical work and energy cost data of 60 healthy subjects (speed: 4 km/h) with artificial LLD induced by soles (2 and 4 cm), 20 patients (speed: 3.75 ± 0.5 km/h) with real LLD and 20 matched subjects (speed: 3.75 ± 0.5 km/h) were collected. Statistical comparisons between the groups were performed using a t-paired test and ANOVA.
Results: Patients with a real LLD showed a significant decrease in mechanical work and energy cost when compared to norms. Patients with real LLD provide a better recovery when compared to subjects with artificial LLD of 2 cm, and a decrease of energy cost and higher muscular efficiency (mechanical work/energy cost) when compared to subjects with artificial LLD of 4 cm.
Conclusions: Our results showed that patients with a real LLD develop compensatory strategies during gait, probably to minimize the displacement of the body center of mass and consequently reduce the amount of energy expenditure useful for their displacement. Moreover, they adopt a better gait strategy compared to the subjects in whom LLD was simulated.

1. Introduction

Walking is the usual mode of human locomotion [1]. However, musculoskeletal pathology may alter our ability to move, disturbing gait, increasing energy costs and, consequently, reducing our autonomy. For example, the use of walking cane in patients with knee osteoarthritis has been observed to cause an increase in energy expenditure during walking [2].

Leg Length Discrepancy (LLD), whether or not linked to a pathological process, is one of the most frequent musculoskeletal conditions encountered in clinical practice. LLD, defined as a condition in which the lower limbs are noticeably unequal in length [3], LLD is identified in as many as 40% [4] to 70% [5] of the population. Two etiological groups can be characterized, based on structural versus functional alterations: structural LLD is defined as real LLD associated with shortening of bony structures; functional LLD is defined as LLD that is the result of altered mechanics of the lower extremities [6].

Several authors have shown that LLD (greater than 20–30 mm) can produce changes in gait. These include increased ground reaction forces [7–9], increased lower extremity kinetic energy [10] and increased mechanical work [11,12], defined as the total positive mechanical work (W_{tot}) done by the muscles during walking, in subjects with real LLD, and increased oxygen consumption (VO_2) in subjects with artificial LLD induced by wearing a shoe with a sole [13].

Song et al. measured mechanical work during gait in children with real LLD. They observed that the children used several techniques to compensate for the LLD, including toe walking, vaulting, circumduction, and increased flexion of the longer limb. In addition, they noted that the longer limb performed more mechanical work than did the shorter. The average LLD for subjects with no observable compensatory strategy was 16.4 mm [12]. To our knowledge, energy expenditure has not been studied in real LLD. Gurney et al. created an artificial LLD

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using shoe soles in healthy older persons (ages 55–86) during gait. The subjects had significantly greater energy consumption at 20, 30 and 40 mm of LLD compared to no LLD [13].

Normal human walking is governed by a multitude of interrelated parameters: kinematics, kinetics and energetics. Understanding these parameters that describe gait biomechanics is essential to improve the functional activity of persons suffering from pathology that affects walking. The role played by energetics, which may be a good indicator of the difficulty a subject has to walk, is often neglected; its evaluation could contribute to better therapeutic decisions for improving gait in individuals with LLD.

We hypothesized that people with real LLD have an altered walking mechanism and adapt their walking strategy to limit excessive energy expenditure better than do people with experimentally artificial LLD.

The current study was therefore designed first to assess the effects of real LLD on mechanical work and energy cost during walking and second to compare the energetic changes in subjects with real and artificial LLD.

2. Method

2.1. Participants

The subjects were divided into three groups. The first was composed of 60 healthy adult subjects aged 18–29 years (22 ± 1 years, group 1) who participated in the experiment, and walked with and without soles of 2 and 4 cm. The second group was composed of 20 young subjects with real LLD aged 5–19 years (12 ± 3 years, group 2). The third group was composed of 20 young subjects (12 ± 3 years, group 3, norm) without LLD matched in age and speed with each subject of group 2. The sex ratio and demographic data of the three groups are shown in Table 1.

Group 1 subjects were recruited from university personnel between January and March 2016. Group 2 subjects were recruited after consultation in the orthopedic service of our hospital between January and December 2016. Subjects with an LLD of less than 1 cm or who had undergone any surgery, fracture or immobilization of the lower limbs in the six months prior to the evaluation were excluded. Group 3 subjects, with no lower limb orthopedic history were recruited from our entourage (professional and social). Subjects less than 5 years of age or with more than 1 cm of inequality or who had trauma to the pelvis or limb in the six months prior to the study were not included.

Every subject or parent gave signed consent and participated freely in the study, which was approved by the local ethics board.

2.2. Procedures

Gait was assessed using a three-dimensional analysis, which included synchronous kinematics, kinetics, mechanical and energetic measurements [14] (Fig. 1).

All subjects walked on a motor-driven treadmill (Mercury LTmed, HP Cosmos®, Germany) equipped with force captors and surrounded by eight infrared cameras at 200 Hz (BTS, Milan, Italy) to measure the trajectories of reflective markers positioned on specific anatomical landmarks.

Table 1
Sex ratioand demographic data.

	Group 1 n = 60 Mean ± SD	Group 2 n = 20 Mean ± SD	Group 3 n = 20 Mean ± SD
Age (Years)	22 ± 1	12 ± 3	12 ± 3
Height (cm)	173.0 ± 8.0	153.3 ± 23.5	157 ± 18.7
Weight (kg)	67.6 ± 9.1	51.5 ± 25.8	39.9 ± 13.0

SD: Standard Deviation.

The subject was fitted with a mask to measure VO_2 and carbon dioxide production (VCO_2) throughout the treadmill test using an ergospirometer (Medisoft, Belgium).

The sessions began with a rest period, in which the subjects stood barefoot for the static calibration of kinematic and energetic variables. Thereafter, the subjects were asked to walk on a treadmill for a few minutes. For group 1, all subjects walked at a constant speed of 4 km h^{-1} for each trial (with and without soles). For group 2, the subjects walked at a spontaneous speed that had been measured earlier using the 10 m walk test [15]. Group 3 subjects walked on the treadmill at different speeds of 1, 2, 3, 4 and 5 km h^{-1} (in order to establish norms). Each subject walked for a few minutes until a steady state was reached and maintained for at least 2 min to record energetic variables. Kinematics and kinetics variables were then recorded simultaneously and averaged over 10 successive strides. The mean for each data was used for statistical analysis.

In group 1, LLD was induced using 2 cm and 4 cm soles (Airlit) attached to a sports shoe. The order in which the soles were used was random and determined by drawing lots. Before gait analysis, the subjects of all groups walked on the treadmill for at least 10 min in a practice session to get used to the treadmill, and also to the different soles for group 1.

2.3. Parameters

Mechanical work was computed as follows: the total positive mechanical work (W_{tot}) done by the muscles during walking was divided into the external work (W_{ext}) performed to move the body Center of Mass (COM) relative to surroundings and the internal work (W_{int}) performed to move the body segments relative to the COM [16].

W_{ext} was computed from four force transducers located at the four corners of the treadmill. These transducers measured the 3D-ground reaction forces according to Cavagna [17]. W_{ext} represents the positive work and is divided into the forward work (W_{ekf}), vertical work (W_{ekv}) and lateral work (W_{ekl}) necessary to accelerate the COM in the three directions and lift the COM during a stride.

The Recovery, quantifying the percentage of mechanical energy saved by a pendulum-like exchange between the gravitational potential energy and the kinetic energy of the COM (i.e., an index reflecting the effectiveness of the pendulum-like mechanical mode of walking), was measured [17,18].

W_{int}, the work required to move the limbs relative to the COM was computed from kinematic data following the methods described by Willems et al. [16] and by Detrembleur et al. [19].

The metabolic cost was determined by the subject's VO_2 and VCO_2. The mass specific gross energy consumption rate (W kg^{-1}) was obtained from the VO2 using the energy equivalent of oxygen, taking into account the measured respiratory exchange ratio (RER). Each energy measurement started with a rest period in which the subject was standing on the treadmill. Thereafter, they walked until a steady state was reached and maintained for at least 2 min. The Joules of energy expended per liter of oxygen consumed was computed depending on the RER according to the Lusk equation [20]. The energy expended above the resting value (standing subtracted from walking consumption) was divided by the walking speed to obtain the net energy cost of walking (C, J/kg m^{-1}) [21]. The efficiency (η) of the positive work production by the muscles was calculated as the ratio between W_{tot} and C [21].

2.4. Statistical analysis

All variables that had a normal distribution and equality of variance are presented as means (± SD). Other variables are expressed as medians and quartiles [25–75%]. Statistical analysis was performed