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Postural adjustment in experimental leg length difference evaluated by means of thermal infrared imaging

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Abstract

Limb length discrepancy (LLD) is defined as a condition in which limbs are unequal. The asymmetric load of body segments secondary to LLD may cause a tonic contraction of back and lower limb muscles, thus resulting in subtle cutaneous temperature variations. The aim of this study was to test the capability of high-resolution thermal infrared (IR) imaging to measure the cutaneous temperature short-term adaptation, potentially associated with 'forced' LLD conditions. An experimental LLD, obtained by placing a 20 mm foot support under the dominant foot, was used. IR imaging on 18 male healthy volunteers was performed in three experimental conditions of standing position: (T_0) neutral posture; (T_1) experimental LLD; (T_2) neutral posture as in T_0. Temperature variations were evaluated on the cutaneous projection of postural muscles bellies. Significant and specific temperature variations among conditions were ipsilaterally observed on the tibialis anterior, gastrocnemius, quadriceps and latissimus dorsi muscles. Specific patterns characterized the cutaneous temperature as a consequence of the muscle activity associated with the posture variation. IR imaging was able to highlight specific functional activations. The method is non-invasive and it can be repeated without any discomfort for the physiopathological and clinical evaluation of LLD patients.

Keywords: thermal infrared imaging, leg length discrepancy, muscle overload, posture

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Limb length discrepancy (LLD) is defined as a condition in which limbs are noticeably unequal (Sabharwal and Kumar 2008). It is a common problem frequently found in the asymptomatic population (Subotnick 1981, Guichet *et al* 1991). According to Woerman and Binder-Macleod (1984), as many as 40–70% could exhibit a physiological discrepancy between the limbs' length. Two pathological forms of LLD have been described: anatomical, i.e. associated with a shortening of bony structures, and functional, i.e. secondary to other musculoskeletal diseases which influence the biomechanics of lower limbs (Gurney 2002). LLD can be present in both acute and chronic forms. The acute form ('forced LLD') may occur in subjects with lower limb fractures (casts) or Achilles tendon ruptures (lower leg braces, orthotics, etc) (Gurney 2002). Chronic LLD may be associated with musculoskeletal disorders, such as scoliosis, pelvic and sacral misalignments, osteoarthritis, etc (Bennell *et al* 1996, Brunet *et al* 1990, Friberg 1983, Greenman 1979, Papaioannou *et al* 1982).

Although LLD is mostly asymptomatic, it may cause either functional or structural dysfunction (Sabharwal and Kumar 2008). The asymmetric load of body segments secondary to LLD has a stressful mechanical effect on different muscles; in particular it may cause a tonic contraction of back and lower limb muscles, such as quadratum lumborum, latissimus dorsi and gastrocnemius. The effects of LLD on the posture have been widely studied by means of gait analysis and balance platforms (Blustein and D'Amico 1985, Mahar *et al* 1985, Bhave *et al* 1999, Blake and Ferguson 1992), while the activity of the single muscles involved, both at rest and during active contraction, has been investigated only by means of electromyography (EMG) (Vink and Huson 1987, Gurney *et al* 2001, Balestra *et al* 2001).

It has been proved that muscular activity induces heat transfer processes among muscles and superficial tissue layers, which in turn results in cutaneous temperature variations (Merla and Romani 2006, Zontak *et al* 1998). Since the maintaining of the orthostatic posture is obtained through the complex activity of anti-gravitational muscles, subtle cutaneous temperature variations are expected with posture change. Modern high-resolution thermal infrared (IR) imaging is able to non-invasively record and precisely quantify cutaneous temperature variations (Merla and Romani 2006). Therefore, high-resolution IR imaging may provide a quantitative evaluation of the cutaneous thermal effects possibly associated with posture change. The aim of this study was to test the capability of IR imaging to properly describe and quantitatively measure the cutaneous temperature short-term adaptation potentially associated with posture change under 'forced LLD' conditions. To achieve this goal, we used an experimental model of 'forced LLD', obtained by placing a 20 mm foot support under the dominant foot.

Our experimental hypothesis was that a significant increase of temperature would occur in those cutaneous regions corresponding to the posterior anti-gravitational and lower limbs muscles, which are closer to the foot support and principally involved in the passage from neutral standing position to 'forced LLD' condition. Therefore, we expected to record a region-specific cutaneous temperature rearrangement associated with the posture change.

Should this hypothesis be verified, IR imaging may be advantageously used to obtain additional functional information to short-term posture adaptation.

2. Material and methods

2.1. Subjects

Eighteen male healthy volunteers (mean age 22.3 ± 2.6 years; range 20–31 years) were enrolled in this study. All the subjects were right-footed, as determined by self-report on the lower limb prevalently used in sport activity. Leg length was measured for each individual according to Beattie's procedure (Beattie *et al* 1990). The inclusion criterion was LLD $<$ 10 mm (Goel *et al* 1997).

The exclusion criterion was the presence of musculoskeletal diseases, potentially related to LLD (low back pain, scoliosis, hip pain, trochanteric bursitis). The local Ethical Committee approved the study. The participating volunteers provided signed consent form prior to being enrolled in the study.

2.2. IR imaging and experimental paradigm

The subjects were asked to observe a series of standardization rules before attending the experimental measurements (Merla and Romani 2006). Specifically, they avoided heavy physical activity and the consumption of unnecessary drugs and treatments in the week preceding the test. Moreover, they abstained from the consumption of vasomotor-active substances (caffeine, smoking, etc) and a heavy meal for a 4 h period prior to the test. Paper markers were put on the naked body, in correspondence with anatomical reference landmarks to facilitate the individuation of the cutaneous projection of the muscles of interest Messeri and Leoni 1990. IR imaging measurements were performed in a controlled environment room (temperature: 23 ± 1 °C; relative humidity: $55 \pm 10\%$, no direct ventilation).

The experimental paradigm started with the subjects in the upstanding relaxed and free position, acclimating to the environment conditions for a 20 min period before acquiring the first set of total body IR images (T_0). A second set of images (T_1) were recorded; after that the subject was observed for a 20 min period in the upright position while wearing a 20 mm synthetic rubber under the right foot. The support was kept during the IR images acquisition as well. At the end of T_1 acquisition, the support was removed and the subject was allowed to assume his natural upright posture for a further 20 min period before acquiring a final series of IR images (T_2).

Total body IR imaging consisted of recording high-resolution thermograms of different body segments from anterior, lateral and posterior views (figure 1). Thirty thermal snapshots were collected for each measurement condition (T_0, T_1 and T_2). IR images were then saved on a picture archive and the communication system for further analysis.

IR imaging was performed by means of a FLIR SC3000 QWIP camera, which operates in the 8–9 μm spectral range, with a 0.02 K temperature sensitivity (NETD at 30 °C). The 320×240 FPA camera was equipped with a 20° lens. The images were acquired with a 1.1 mrad spatial resolution.

2.3. Data analysis

IR images were analysed using the Thermacam Researcher Professional 2.9 Software (FLIR©). The average and the standard deviation of the temperature for any user-selected cutaneous region of interest (ROI) were computed. ROIs were bilaterally identified through the landmark position and manually selected by the operator, who ignored the experimental conditions and paradigm.

The following ROIs, representing the skin projection of the muscle bellies, were selected (figure 1): (1) abdominal; (2) quadriceps femoris; (3) tibialis anterior; (4) gatrocnemius; (5) leg flexors; (6) tensor fasciae latae; (7) quadratum lumborum; (8) latissimus dorsi and (9) trapezius.

2.4. Statistical analysis

The statistical analysis was performed to compare differences in cutaneous temperature distribution for the given ROIs across the experimental phases. For an easier data processing

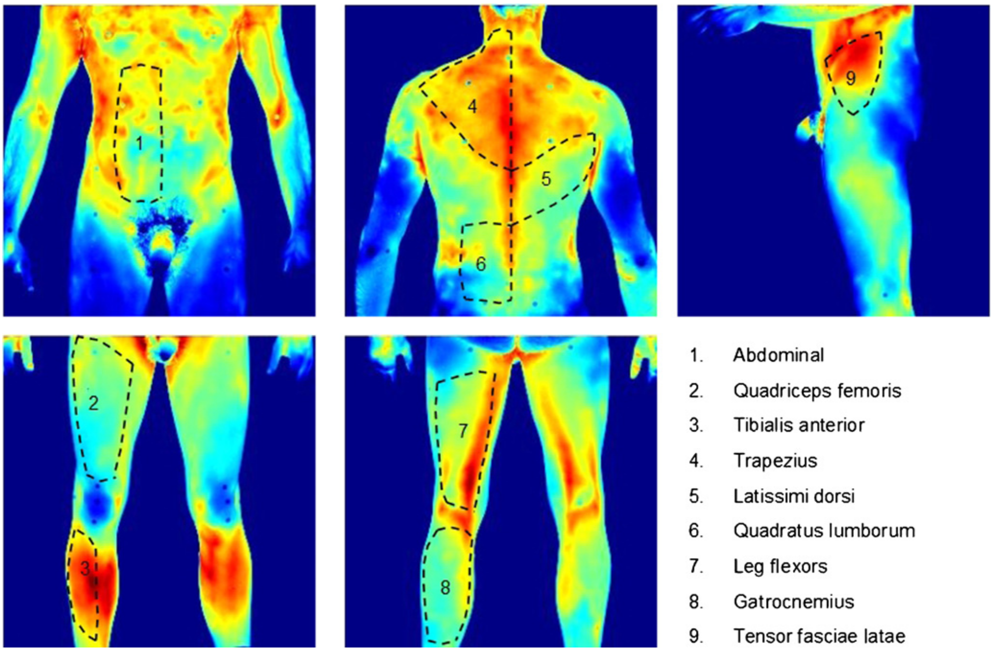

Figure 1. Total body IR imaging. The dot lines represent the cutaneous projection of the muscle structures involved in maintaining posture and individuate the regions of interest (ROIs).

report, the comparisons T_0 versus T_1, T_1 versus T_2 and T_0 versus T_2 were termed $T_{0\text{–}1}$, $T_{1\text{–}2}$ and $T_{0\text{–}2}$, respectively.

Temperatures recorded in the successive experimental phases for each ROI were compared through one-way ANOVA for repeated measures (Zar 1999). $F_{0.05,2,34}$ was assumed as a reference threshold for the statistical significance of the test. To carry out multiple comparisons between the different experimental phases, the Holm test (Holm 1979) corrected for repeated measures was performed for those ROIs which exhibited significant differences at the comparison $T_{0\text{–}1}$, $T_{1\text{–}2}$ and $T_{0\text{–}2}$. The significance levels for the Holm test were determined as 0.017, 0.025 and 0.05.

The comparison between temperature distributions for agonist and antagonist ROIs was carried out according to the same procedure.

3. Results

Figure 2 shows how the cutaneous temperature of lower limbs varied across the several experimental phases for a randomly chosen subject. Grand average and standard deviation values for each ROI temperature are reported in table 1.

3.1. Right-side ROI temperatures versus time

$T_{0\text{–}1}$ significant temperature variations were observed for the tibialis anterior, quadriceps and latissimus dorsi. For $T_{0\text{–}2}$, only the gastrocnemius showed a statistically significant difference.

Table 1. ROI, mean temperature, standard deviation and level of significance for each experimental phase is reported.

ROI		Experimental phase Mean temperature (°C) (standard deviation) T_0	T_1	T_2	Statistical significance $p < 0.05$ $T_{0–1}$	$T_{1–2}$	$T_{0–2}$
Tibialis anterior	Right	30.3 (1.3)	30.7 (1.3)	30.6 (1.1)	0.008		
	Left	30.2 (1.2)	30.7 (1.1)	30.8 (0.8)	0.002		0.006
Gastrocnemius	Right	30.1 (1.2)	30.2 (1.2)	30.5 (1.0)			0.013
	Left	30.1 (1.3)	30.4 (1.3)	30.5 (0.1)			0.005
Quadriceps	Right	29.5 (1.6)	29.8 (1.5)	29.8 (1.4)	0.021		
	Left	29.8 (1.5)	29.5 (1.6)	29.5 (1.5)			0.011
Latissimus dorsi	Right	31.1 (1.2)	31.5 (1.3)	31.2 (1.1)	0.015		
	Left	31.2 (1.2)	31.5 (1.2)	31.3 (1.2)	0.001		
Quadratum lumborum	Right	31.1 (1.4)	30.1 (1.4)	31.2 (1.2)			
	Left	31.1 (1.4)	30.1 (1.4)	31.1 (1.2)			
Abdominals	Right	31.3 (1.3)	31.1 (1.3)	31.1 (1.1)			
	Left	31.3 (1.3)	31.1 (1.2)	31.1 (1.1)			
Leg flexors	Right	30.3 (1.3)	30.2 (1.2)	30.2 (0.8)			
	Left	30.4 (1.3)	30.2 (1.2)	30.4 (1.1)			
Trapezius	Right	32.2 (1.2)	31.2 (1.2)	32.0 (1.0)			
	Left	32.2 (1.2)	31.2 (1.2)	32.0 (0.1)			
Tensor fasciae latae	Right	31.4 (1.3)	31.6 (1.3)	31.5 (1.1)			
	Left	31.3 (1.4)	31.4 (1.5)	31.3 (1.2)			
Tibialis anterior (TA) versus gastrocnemius (G)	Right TA	30.3 (1.3)	30.7 (1.3)	30.6 (1.1)	0.017	0.02	
	Right G	30.1 (1.2)	30.2 (1.2)	30.5 (1.0)			
	Left TA	30.2 (1.2)	30.71 (1.1)	30.8 (0.8)			
	Left G	30.1 (1.3)	30.4 (1.3)	30.5 (0.1)			
Quadriceps (Q) versus leg flexors (LF)	Right Q	29.5 (1.6)	29.8 (1.5)	29.8 (1.4)			
	Right LF	30.3 (1.3)	30.2 (1.2)	30.2 (0.8)			
	Left Q	29.8 (1.5)	29.5 (1.6)	29.5 (1.5)			0.001
	Left LF	30.4 (1.3)	30.2 (1.2)	30.4 (1.1)			

No significant differences were observed for the abdominals, trapezius, quadratum lumborum, leg flexors and tensor fasciae latae in all the experimental phases.

3.2. Left-side ROI temperature versus time

Tibialis anterior and latissimus dorsi showed statistically significant $T_{0–1}$ temperature variations. Significant differences were also observed for the tibialis anterior, gastrocnemius and quadriceps for $T_{0–2}$. As for the right-side ROIs, no differences were observed for the abdominals, trapezius, quadratum lumborum, leg flexors and tensor fasciae latae in all the experimental phases.

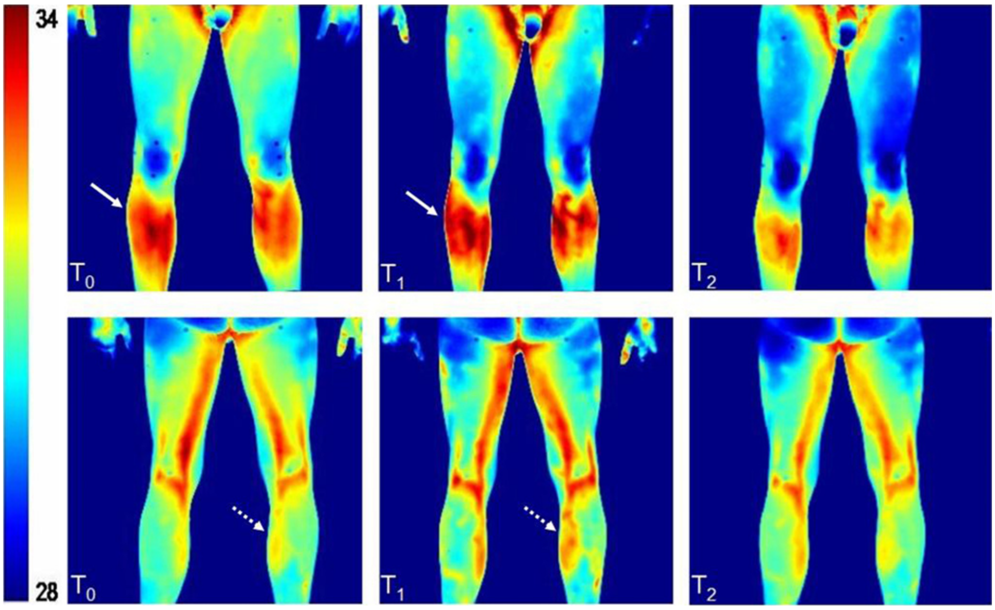

Figure 2. IR imaging of lower limb temperature variation for a randomly chosen subject: anterior and posterior views taken at T_0, T_1 and T_2. Right tibialis anterior and right gastrocnemius exhibit the largest temperature variation across the experimental phases.

3.3. Agonist versus antagonist low limb ROIs

The analysis compared tibialis anterior versus gastrocnemius temperature differences and quadriceps versus leg flexors temperature differences across the experimental phases. Statistically significant $T_{0\text{–}1}$ ($p = 0.017$) and $T_{1\text{–}2}$ ($p = 0.02$) differences were found in right tibialis anterior and right gastrocnemius. Only the $T_{0\text{–}2}$ difference was statistically significant for the left quadriceps versus leg flexors ($p = 0.000\,01$).

4. Discussion

In this paper we used high-resolution thermal infrared imaging to evaluate the cutaneous thermal effects on lower limbs induced by an experimental ‘forced LLD’. The proposed experimental condition, obtained by applying a 20 mm support under the dominant foot, closely resembles common pathological situations, such as ambulation with lower limb brace after rupture of Achilles tendon or with casts for leg fractures.

The experimental LLD determined the bilateral activation of specific thermal patterns for the cutaneous projections of the tibialis anterior, gastrocnemius, quadriceps and latissimus dorsi. The cutaneous projection of the abdominal, trapezius, quadratum lumborum and leg flexors did not show any specific thermal patterns.

The largest temperature variations were observed in the tibialis anterior and gastrocnemius ROI. Such a result agrees with our experimental hypothesis that a significant increase of temperature would occur in those cutaneous regions corresponding to the posterior anti-gravitational and lower limbs muscles, which are closer to the foot support and principally involved in the passage from neutral standing position to ‘forced LLD’ condition. All the considered ROIs but tibialis anterior, gastrocnemius and quadriceps recovered their basal average temperature with the removal of the foot support.

The results of our study agree with those obtained evaluating the muscular activity by means of EMG, which evaluates the phenomenon from a different physiopathological point of view. In subjects with a 'forced' experimental LLD, Gurney *et al* (2001) observed a significant increase in the EMG activity of quadriceps femoris, gastrocnemius, plantar flexor and back extensor muscles. These features have been confirmed by Vink *et al* (1987), who reported also an increased EMG activity of the intrinsic lumbar back muscles. The observed EMG activity can be related to the activation of the anti-gravitational muscles, which occurs when LLD is present. As a consequence, some muscles are contracted while others are relaxed to counterbalance the postural disorder (Vink and Huson 1987).

On the basis of the concordance between increased EMG activity and increased cutaneous temperature for a given ROI, it may be inferred that the increased cutaneous temperature in selected ROIs may be considered as a by-product of the underlying muscles activation.

Why an increased muscular activation related to posture variation could result in an increased temperature in specific cutaneous ROIs is matter of debate. In fact, where it has been largely proved that dynamic physical exercise produces cutaneous temperature changes (Zontak *et al* 1998, Ferreira *et al* 2008, Merla *et al* 2005) and that the sympathetic nervous system is a major determinant of skin temperature (Gold *et al* 2009), there is no prior knowledge about the cutaneous thermal effects associated with the simple variation of the orthostatic posture. It may be supposed that the increased metabolism and heat produced in the muscles involved in the balance and posture control may be transferred to cutaneous layers by means of loco-regional vasodilation and sympathetic activation.

The larger and more significant thermal effects observed in tibialis anterior and gastrocnemius than other ROIs can be explained by a more rapid adaptation to the postural perturbation of these muscles, which are relatively smaller, nearer to the foot support and, therefore, more affected by the posture variation. More massive and distant muscles (back and leg muscles) likely require longer activation time and larger posture variation to cumulate and transfer heat to the cutaneous layer. In addition, their geometry may be less affected by the foot support.

The experimental design and procedure proposed in this paper present some limitations to the understanding of the underlying physiology of the found results. The first one is that we did not perform EMG simultaneously to IR imaging. The reason is that EMG patches could cover significant ROIs portion and therefore interfere with the proper estimation of the ROI temperature.

A further weakness is related to the choice of the lasting period of the experimental protocol phases. Further studies are needed to evaluate the effects induced by both shorter (i.e. rapid adaptation) and longer protocol phases (i.e. the effects of upright standing on muscular fatigue).

The results obtained through the proposed experimental model cannot be applied to chronic LLD, since it has been shown that no muscular overload can be observed in long-term LLD patients (i.e. since childhood), where functional adjustments could occur, so that a satisfactory functional *modus operandi* is achieved (Burke 2004).

In any case, the results of our study prove that high-resolution IR imaging may represent a suitable method to study forced LLD. IR imaging has been able to highlight the specific functional activation which occurs in several postural muscles. This information can be useful in the clinical practice for rehabilitation purposes and for preventing pain or other injury.

The method is easy to perform, non-invasive and touchless and it can be repeated without any discomfort for the subject (Tucker 2000, Zhang *et al* 2009), thus helping the follow up of the patients.

In conclusion, IR imaging is a technique which may be effectively added to the existing techniques, for the assessment of LLD and postural disorders, and even for clinical purposes. In particular, it can be useful in the evaluation of patients affected by hip fractures or submitted to lower limb surgery (casts). It can also be used for the follow-up and evaluation of different treatments, such as physical therapy and arch support.

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