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Electromyographic activity imbalances between contralateral back muscles: An assessment of measurement properties

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Abstract—Electromyographic (EMG) contralateral imbalances of back muscles are often interpreted as an aberrant back muscle pattern related to back pain. This study assessed different measurement properties (influence of the control of asymmetric efforts and of the force level, reliability, and sensitivity to low back status) of EMG imbalance parameters. Healthy controls (n = 34) and chronic low back pain subjects (n = 55) stood in a dynamometer measuring the principal (extension) and coupled (lateral bending, axial rotation) L5/S1 moments during isometric trunk extension efforts. The results showed that back pain subjects did not produce higher coupled moments than controls. Providing feedback of the axial rotation moment to correct asymmetric efforts during the task did not reduce EMG contralateral imbalances, except for some extreme cases. Normalized EMG imbalance parameters remain relatively constant between 40% and 80% of the maximal voluntary contraction. The reliability of EMG imbalance parameters was moderate, at best. Finally, neither low back status nor pain location had an effect on EMG contralateral imbalances. We conclude that the clinical relevance of EMG contralateral imbalances of back muscles remains to be established.

Key words: asymmetry, back pain, dynamometry, electromyography, force level, lumbar impairment, muscle imbalance, pain location, reliability, visual feedback.

INTRODUCTION

The appropriate management of low back pain necessitates the development of objective measurements of low back status. Considering the poor relationship between clinical observation, imaging findings, and symptoms [1–2], measurements of lumbar impairments need to be developed. Research on the evaluation of lumbar impairments with surface electromyography (EMG) point to some aberrant back muscle patterns such as hypo- or hyperactivity [3], the absence of the flexion-relaxation phenomenon [4–6], and EMG contralateral imbalances [7].

Abbreviations: ANOVA = analysis of variance, CI = compensated imbalance, CLBP = chronic low back pain, EMG = electromyography, ICC = intraclass correlation coefficient, IL-L3 = iliocostalis lumborum at L3 level, LO-L1 = longissimus at L1 level, M_{ext} = moments in extension, MF = median frequency, LO-T10 = longissimus at T10 level, M_{lat} = moments in lateral bending, M_{rot} = moments in axial rotation, MU-L5 = multifidus at L5 level, MVC = maximal voluntary contraction, RMS = root-mean-square, SD = standard deviation, SEM = standard error of measurement, UI = uncompensated imbalance, VAS = visual analog scale.

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Some authors hypothesize that contralateral imbalances, prior or secondary to back pain, produce mechanically induced back pain by loading the spine incorrectly [8–9]. However, EMG contralateral imbalances might be the result of several factors unrelated to back pain per se.

Various explanations are given to explain the alternating or uneven EMG activity between different parts of the erector spinae, such as, insufficient control of lateral bending and/or axial rotation efforts [10–13], postural imbalances [14], the inhibition of muscle activation secondary to pain [15–16], a mechanism to delay muscle fatigue [17], and an alteration of muscle physical properties due to training or handedness [10,13,18–19]. However, before ascertaining that EMG contralateral imbalances of back muscles are related to back muscle impairment or to any other mechanism, we must control some other factors that could be related to pain behaviors such as asymmetric postures and efforts.

Recently, our group developed a triaxial static dynamometer to control coupled lumbar moments (lateral bending, axial rotation) during trunk extension tasks [20]. These development efforts might respond to a point highlighted by Grabiner et al., who noted that the universal assumption in the design of trunk dynamometers assumes that coupled moments are negligible during trunk efforts exerted in the sagittal plane [8]. From our point of view, the minimization of coupled moments should reduce the variation in load sharing between contralateral muscles of the back and consequently increase the reliability of EMG measurements of back muscle function. This should be particularly true for chronic low back pain (CLBP) subjects who might develop compensation strategies involving coupled moments to reduce their back pain or to compensate for weakness on one side. Patients suffering from unilateral back pain could be even more prone to produce such coupled moments. This might get worse with an increasing level of exertion because pain would be exacerbated.

Another important issue clinicians or researchers should remember when assessing back muscles of CLBP patients is to standardize the level of effort so that different subjects can be compared. This is usually performed by setting the force level relative to a maximal voluntary contraction (MVC), such as during EMG-based fatigue tests where a relative force level is set at 75 or 80 percent MVC [21–22]. However, CLBP patients are reluctant to produce MVCs because of pain or fear of injury. The comparison of back muscle fatigue of healthy and CLBP subjects with the use of such measurement protocols has led to counterintuitive results [21–22]. Therefore, to clarify their clinical relevance, we need to evaluate whether the EMG imbalance parameters are free from the influence of force level.

The EMG spectral indices presumably sensitive to left-right differences are generally not reliable [23–25]. This finding suggests that either the phenomenon of EMG left-right imbalances does not exist (a consequence of poorly controlled extension tasks) or the EMG measurement itself is not sensitive enough to provide a reliable picture of this phenomenon. However, the reliability of EMG imbalance parameters based on the amplitude of the signal has never been assessed. In addition, new left-right ratio parameters have been proposed [22] but have not yet been evaluated. Investigators should do such a reliability analysis under controlled assessment conditions (symmetric efforts) along with a comparison between healthy and CLBP subjects to better evaluate the relevance of these EMG parameters.

The present study tested the use of EMG activity imbalances between contralateral muscles as a back impairment indicator. For this purpose, we needed to verify whether EMG contralateral imbalances are (1) affected by an inadequate control of coupled moments, (2) influenced by the force level of back muscle contraction, (3) reliable in controlled (symmetric) trunk extension efforts, and (4) sensitive to the low back status (healthy vs. CLBP subjects) and pain location (left, right, middle) of the subjects.

METHODS

Dynamometry

The dynamometer consisted of a triaxial force platform (Advanced Mechanical Technology, Incorporated [AMTI], Watertown, Massachusetts] model MC6-6-1000) mounted on a steel frame that allows stabilization of the feet, knees, and pelvis (**Figure 1**) [20]. The subjects stood in the dynamometer with their trunks erect and knees straight. Trunk extension was generated against a padded bar fixed on the surface of the force platform and adjusted at the T4 level. The dynamometer measures L5/S1 moments in extension (M_{ext}), lateral bending (M_{lat}), and axial rotation (M_{rot}). During each extension effort, M_{ext} was displayed in real time as visual feedback on a monitor positioned in front of the subjects. The visual feedback consisted of a vertically moving square target with lower

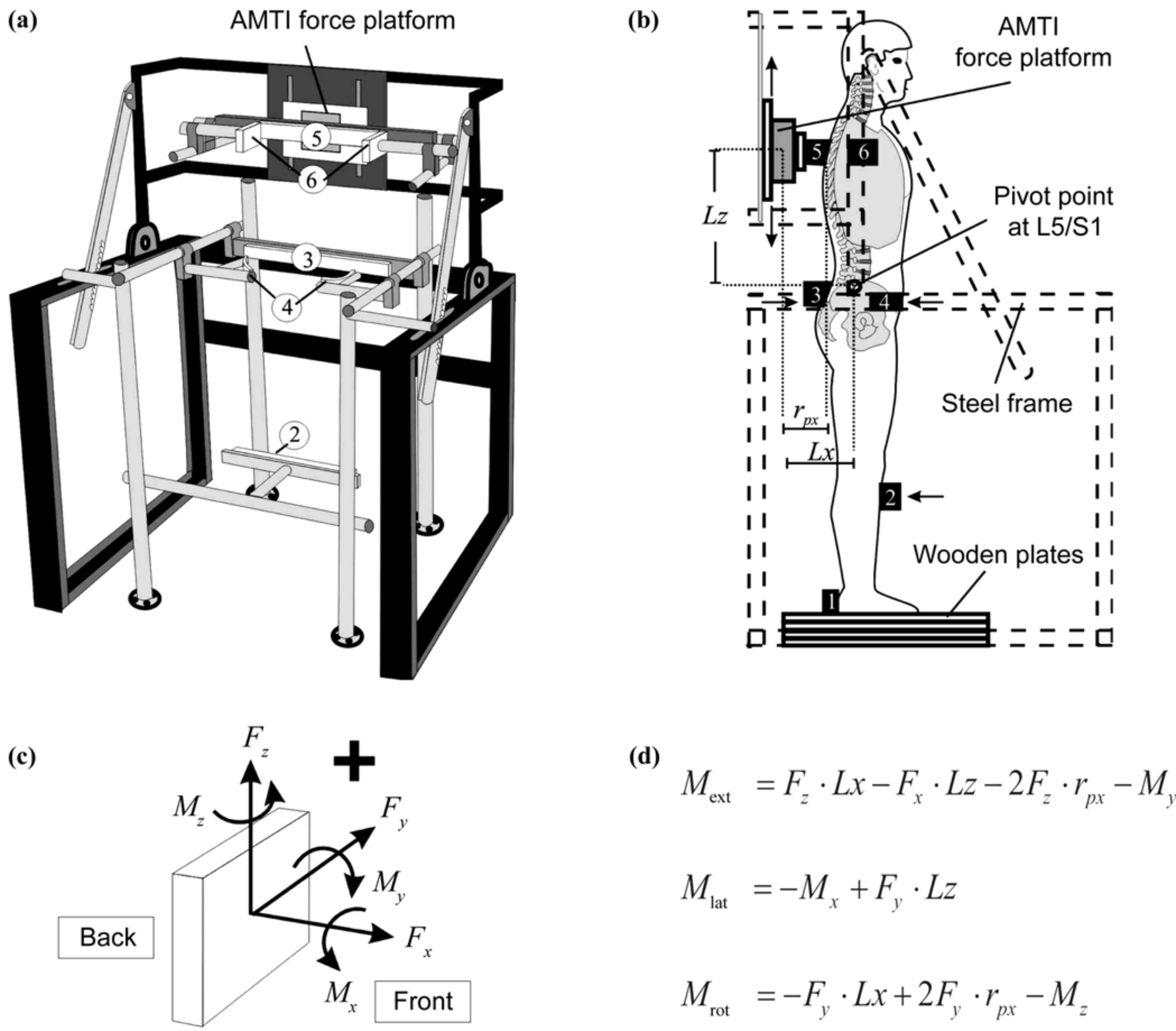

Figure 1.
Diagrams of **(a)** dynamometer structure, **(b)** subject positioning, **(c)** sign convention of the force platform, and **(d)** L5/S1 moment equations. More details in Larivière C, Gagnon D, Gravel D, Bertrand Arsenault A, Dumas J, Goyette M, Loisel P. A triaxial dynamometer to monitor lateral bending and axial rotation moments during static trunk extension efforts. Clin Biomech. 2001;16(1):80–83. For simplicity, only black frame shown in **(a)** is represented (with broken lines) in **(b)**. In **(b)**, adjustable components (pads and force platform) are represented by arrows. Pads are numbered for better understanding correspondence between **(a)** and **(b)**. AMTI = Advanced Mechanical Technology, Inc.

and upper bounds corresponding to a tolerance limit of 10 percent of the M_{ext} and with lateral bounds corresponding to a tolerance limit of 15 Nm to control for M_{rot}. A trial was accepted only when the target was respected (see the corresponding M_{ext} signal in **Figure 2**). Otherwise, the trial was discarded and a new attempt was made. Subjects only required a few attempts to get accustomed to this task. In the present study, M_{rot} feedback was provided or not according to the experimental conditions (tasks) described in the following sections.

Subjects and Tasks

We used five samples of subjects in the present study (**Table 1**). The dataset from a previous study [20] was

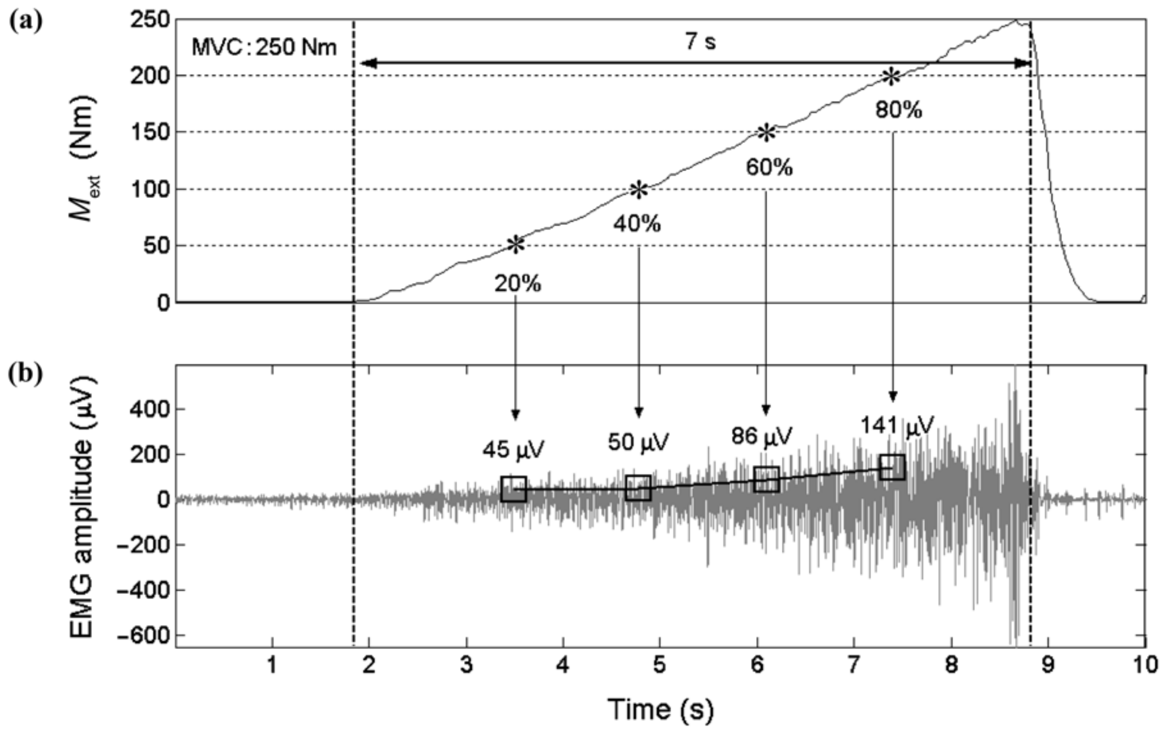

Figure 2.
Illustration of **(a)** L5/S1 extension moments and **(b)** corresponding raw electromyographic (EMG) signal from left iliocostalis muscle corresponding to a typical 7 s ramp contraction. Progressive (smooth) increase in moments in extension (M_{ext}) was possible through use of visual feedback (details in "Methods section"). The 20%, 40%, 60%, and 80% maximal voluntary contraction (MVC) force levels were first identified (asterisks in **(a)**) to position 250 ms time windows on raw EMG signals (represented by lateral position of squares in **(b)**). Then, we performed EMG analyses to compute corresponding root-mean-square (RMS) and median frequency values (RMS values are represented by vertical position of squares in **(b)**).

used as the first subject sample (n = 14 healthy males) to obtain L5/S1 moments during the 7 s ramp trunk extension efforts (details follow) without M_{rot} feedback. A subject sample composed of 35 male CLBP subjects performed ramp contractions with and without M_{rot} feedback. This group was divided into two subgroups, depending on the location of their pain: (1) unilateral pain on the left or right (n = 14; sample 2) or midline of the back (directly on the spinal column: n = 21; sample 3). None of the subjects presented pain localized bilaterally. The fourth (n = 20 healthy males) and fifth (n = 20 male CLBP subjects) subject samples, used in a previous study, provide the data for the assessment of the reliability of different EMG variables [23]. Finally, we used a sixth subject sample, grouping samples 2, 3, and 5 (total = 55 CLBP subjects) to evaluate the sensitivity to low back status.

Inclusion criteria for the healthy subjects were that they have had no back problem or physical disability. Inclusion criteria for the CLBP subjects were lumbar or lumbosacral pain with or without proximal radicular pain (limited distally to the knees) and the presence of chronic pain, defined as a daily or almost daily pain for at least 3 months. Exclusion criteria for the healthy subjects were having back pain in the preceding 6 months or exceeding 1 week at any time in the past, missing at least 1 work day because of back pain, and consulting a clinician for a back problem. CLBP or healthy subjects with prior surgery of the pelvis or spinal column or with scoliosis were also excluded. All CLBP subjects were working during the period when they were evaluated. All subjects were informed of the experimental protocol and of its potential risks and were given written consent prior to their participation. The ethics committee of the Montreal Rehabilitation Institute approved the study and consent form.

On the day of testing, to obtain a general appreciation of their low back status (**Table 1**), we had the CLBP subjects complete different self-administered questionnaires: the Oswestry questionnaire [26] to assess the perception of functional status, a 10 cm visual analog scale (VAS) to score back pain intensity, a pain drawing diagram to

Table 1.
Demographic and some clinical characteristics (mean ± standard deviation) of different samples of subjects used to assess questions.

Characteristic	Sample 1 Healthy (n = 14)	Sample 2 CLBP Unilateral Pain (n = 14)	Sample 3 CLBP Midline Pain (n = 21)	Statistical Test* (p-Value) Samples 1 vs. 2 vs. 3 or 2 vs. 3	Sample 4 Healthy (n = 20)	Sample 5 CLBP (n = 20)	t-Test (p-Value) Samples 4 vs. 5	Sample 6 CLBP (n = 55)	t-Test (p-Value) Samples 4 vs. 6
Age (yr)	33 ± 11	40 ± 10	38 ± 11	0.197	38 ± 13	41 ± 14	0.506	39 ± 13	0.719
Height (m)	1.77 ± 0.05	1.80 ± 0.07	1.77 ± 0.06	0.269	1.75 ± 0.04	1.77 ± 0.08	0.339	1.78 ± 0.07	0.080
Mass (kg)	73 ± 13	82 ± 11	83 ± 10	0.043	73 ± 9	80 ± 13	0.057	81 ± 12	0.004
Oswestry (%)†	NA	21 ± 14	18 ± 11	0.624	NA	18 ± 14	NA	19 ± 13	NA
Pain Intensity (cm)‡	NA	3.4 ± 2.5	2.1 ± 2.2	0.062	NA	1.9 ± 2.4	NA	2.3 ± 2.4	NA
FABQw§	NA	7.6 ± 4.3	7.8 ± 5.1	0.921	NA	9.5 ± 6.4	NA	8.4 ± 5.4	NA
FABQp§	NA	12.1 ± 9.4	15.0 ± 11.1	0.543	NA	13.3 ± 13.7	NA	13.6 ± 11.6	NA
Pain Duration (mo)¶	NA	85 ± 108	71 ± 78	0.958	NA	80 ± 120	NA	79 ± 102	NA

*One-way analysis of variance or t-test (or Wilcoxon test) when only Samples 2 and 3 were compared.
†Perceptions of functional disability were assessed with Oswestry questionnaire. *Source*: Fairbank JC, Couper J, Davies J, O'Brien JP. The Oswestry low back pain disability questionnaire. Physiotherapy. 1980;66(8):271–73.
‡Pain intensity was assessed with a 10 cm visual analog scale.
§Fear-Avoidance Beliefs Questionnaire (FABQ) (*Source*: Waddell G, Newton M, Henderson I, Somerville D, Main CJ. A Fear-Avoidance Beliefs Questionnaire (FABQ) and the role of fear-avoidance beliefs in chronic low back pain (CLBP) and disability. Pain 1993;52(2):157–68), part 1 related to work (FABQw) activities, and part 2 related to physical (FABQp) activities, as measured in the first session.
¶Duration of low back pain (daily or almost daily) as roughly approximated from CLBP subjects' memory.
NA = not applicable.

locate their back pain (current pain on the day of testing), and the fear avoidance beliefs questionnaire [27] to assess fear avoidance behaviors. We also obtained an approximation of back pain duration based on patient memory.

After the EMG electrodes were positioned and the subject was stabilized in the static dynamometer, the subject performed two to four submaximal trunk extension efforts to get accustomed to the apparatus. Then the subject performed static extension efforts using the real-time L5/S1 M_{ext} as visual feedback. Subjects performed some tasks with or without the use of an additional visual feedback to minimize M_{rot}. The first subject sample performed one MVC followed by three 7 s ramps (0%–100% MVC) without M_{rot} feedback. Only the first ramp was used for further analyses. Samples 2 and 3 performed two MVCs (the best of the two was retained as the reference value), one ramp contraction without M_{rot} feedback, three ramp contractions with M_{rot} feedback, and one static trunk extension fatigue task at 75 percent MVC of 30 s duration (with M_{rot} feedback). Only the first (without M_{rot} feedback) and second (with M_{rot} feedback) ramp contractions as well as the fatigue task were used for further analyses. For ramp contractions, we always presented the condition "without M_{rot} feedback" before the condition "with M_{rot} feedback" to keep the subject unaware of the production of asymmetric efforts. Subject Samples 3 and 4 performed the same tasks as Sample 2 (except the ramp without M_{rot} feedback) but were assessed on three sessions at least 2 days apart within a 2-week period. In all the measurement protocols, at least 2 minutes of rest were given between efforts.

Electromyography

We did not collect EMG data for the first sample of 14 healthy subjects. The description of the surface EMG electrodes and their positioning is detailed elsewhere [28]. Briefly, eight pairs of active surface electrodes (Model DE-2.3, DelSys Inc., Wellesley, Massachusetts) were positioned bilaterally on the multifidus at the L5 level (MU-L5), on the iliocostalis lumborum at L3 (IL-L3), and on the longissimus at the L1 (LO-L1) and T10 (LO-T10) levels. The EMG signals from the recording sites were bandpass-filtered (20–450 Hz), preamplified (gain: 1,000), analog to digitally converted at a sampling rate of 2,048 Hz, and stored on a hard disk for later analysis.

Data Processing and Statistical Analyses

For each ramp contraction, we used the EMG (250 ms time window) at each 20 percent force level from 20 to 80 percent MVC in extension to compute root-mean-square (RMS) values (n = 4) and to apply spectral analyses (512 points, Hanning window processing, fast Fourier transform) to extract the corresponding median frequency (MF) values (n = 4). An example of the quality of the signals (M_{ext}, raw EMG, extracted RMS values) obtained with this type of contraction is illustrated in **Figure 2**. For the 30 s fatigue task, the EMG RMS and MF values were computed from a series of successive 250 ms time windows of EMG data. We retained only the portion of the contraction where M_{ext} was stabilized for these analyses so that up to 120 time windows were used to compute EMG imbalance parameters. For each ramp as well as for the fatigue test, the M_{lat} and M_{rot} L5/S1 moments coupled to extension efforts that corresponded to each 250 ms time window of EMG data were retained for further analyses.

We computed EMG imbalance parameters, for each pair of back muscles (MU-L5, IL-L3, LO-L1, LO-T10) and each time window (ramp contraction: n = 4; fatigue contraction: n = up to 120), as the difference between the left and right RMS ($\Delta RMS = RMS_{right} - RMS_{left}$) or MF ($\Delta MF = MF_{right} - MF_{left}$) values. Likewise, ratio parameters ($ratio_{L5}$, $ratio_{L3}$, $ratio_{L1}$, $ratio_{T10}$) were also computed, as detailed previously [22] (e.g., $RMSratio_{L5} = RMS_{L5\_right}/RMS_{L5\_left}$ or $MFratio_{L5} = MF_{L5\_right}/MF_{L5\_left}$). We transformed each ratio to provide values with symmetrical properties centered around 0 [22] as

$$R = \begin{cases} ratio - 1, & ratio \geq 1 \\ -\left(\dfrac{1}{ratio} - 1\right), & ratio < 1 \end{cases} .$$

For the ramp contraction, we computed these EMG imbalance parameters (ΔRMS, ΔMF, RMSratio, MFratio) at each force level (n = 4) using only one RMS or MF value (from one 250 ms time window) at a time. However, for the fatigue task, we computed the average of all the values (up to 120 values) to represent the whole fatigue task, as proposed by Oddsson and De Luca [22]. We multiplied the average RMSratio and MFratio values by 100 to represent the percent difference between the right and left sides, a negative value meaning that the left side was larger than the right side. Two global EMG parameters (uncompensated imbalance [UI] and compensated imbalance [CI]) were also computed from the local RMSratio and MFratio parameters:

$$UI = \frac{|ratio_{L5}| + |ratio_{L3}| + |ratio_{L1}| + |ratio_{T10}|}{4} .$$

$$CI = \frac{ratio_{L5} + ratio_{L3} + ratio_{L1} + ratio_{T10}}{4}$$

Contrary to ratio-based parameters, simple difference-based EMG parameters (e.g., ΔRMS) suffer from a lack of EMG normalization. To solve this problem, we also computed the normalized version of the difference-based parameter as

$$Normalized\_\Delta RMS = \left(\frac{RMS_{right} - RMS_{left}}{(RMS_{right} + RMS_{left}) \div 2}\right) \times 100 .$$

Another issue that merits attention in the use of EMG imbalance parameters distributed around zero (positive and negative values) was the option of using their absolute values (hereafter denoted with the variable's name between vertical bars, e.g., $|RMSratio|$) or preserving the correct sign. When the pain site (left or right) was considered important, as suggested by previous results [15,22], we decided to assess both options. Thus, the coupled M_{lat} and M_{rot} and EMG imbalance parameters were all converted to absolute (positive) values in Questions 1 and 2 (details discussed later), while both avenues (with the correct sign or with absolute values) were evaluated in Questions 3 and 4.

The comparisons necessary to fulfill the objectives of the present study were associated with a specific question. For each question, the subject samples, tasks used, and statistics will be detailed. For most comparisons, the data were not normally distributed and simple transformations (logarithmic, square root, etc.) were inefficient for obtaining a normal distribution. Consequently, nonparametric statistical techniques were applied. However, there is no nonparametric equivalent to two-way analyses of variance (ANOVAs) involving at least one repeated factor. Thus, we needed to test one factor at a time, as detailed later in this paper. All statistical comparisons were performed with Number Cruncher Statistical System 2004 software (Kaysville, Utah).

For Questions 1 and 2, we used ramp contractions. This allowed us to assess the effect of force level using a minimum of contractions (instead of a series of step contractions), thus minimizing the buildup of muscle fatigue during the experiment, but this strategy also had drawbacks (see "Discussion"). EMG imbalance assessments are usually performed with the use of a sustained contraction at a given force level. Oddsson and De Luca used either a 40 percent MVC or an 80 percent MVC fatigue task sustained for 30 s [22]. Thus, we chose to study the measurement properties (reliability in Question 3, sensitivity to low back status in Question 4) of EMG imbalance parameters corresponding to this type of task (here: 75%

MVC sustained for 30 s) to better generalize the results to the protocols usually used for this type of assessment.

Question 1: Do CLBP Subjects Produce Larger Coupled Moments (M_{lat} and M_{rot}) Than Healthy Subjects During an Extension Task and Is the Force Level Important?

We compared results from Samples 1, 2, and 3 using the ramp contractions to assess the effect of force level. Only the $|M_{lat}|$ and $|M_{rot}|$ values corresponding to the ramp performed without providing M_{rot} feedback were assessed. We logarithmically transformed the $|M_{lat}|$ and $|M_{rot}|$ values to obtain a normal distribution. We used two-way ANOVA (Group × Force Level) with repeated measurements of the Force-Level factor to assess differences between groups (three groups: 14 healthy, 14 CLBP subjects with unilateral pain, and 21 CLBP subjects with midline pain) and between force levels (four levels: 20%, 40%, 60%, and 80% MVC).

Question 2: Does Providing a Visual Feedback in M_{rot} Decrease Coupled Moments and EMG Contralateral Imbalances and Is the Force Level Important?

We performed these analyses with Samples 2 and 3 using the ramp contractions (with and without M_{rot} feedback) to assess the effect of force level. To address the effect of feedback, we performed a Wilcoxon matched-pairs signed test (results from all force levels and/or muscle pairs grouped together, depending on the variable) to contrast the results of the two ramp contractions (with and without M_{rot} feedback) for each sample of subjects separately (14 CLBP subjects with unilateral pain and 21 CLBP subjects with midline pain). The effect of force level was assessed, on the same variables, with the Friedman test (results from both feedback modes and both groups grouped together).

Question 3: Are EMG Imbalance Parameters Reliable?

To address reliability, we used the datasets (3 days of measurement) from Samples 4 and 5. The intraclass correlation coefficients (ICCs) and the standard error of measurement (SEM) of each EMG imbalance parameter computed from the fatigue task were calculated. We calculated ICCs and SEMs using the different sources of variances (Subject, Day, Subject × Day) computed from a one-way ANOVA with repeated measurements on the Day factor by using

$$\text{ICC} = \frac{\sigma_S^2}{\sigma_S^2 + \sigma_D^2 + \sigma_{SD}^2} \quad \text{and} \quad \text{SEM} = \sqrt{\sigma_D^2 + \sigma_{SD}^2} \;,$$

where σ_S^2, σ_D^2, and σ_{SD}^2 are Subject, Day, and Subject × Day variances, respectively. ICCs were interpreted as <0.40: poor, 0.40 to 0.75: moderate, and >0.75: excellent [29]. The SEM was expressed as a percentage of the grand mean (across days). We computed the percentage of the total variance explained by σ_D^2 to evaluate the importance of the systematic error associated with the day factor.

Question 4: Are the EMG Imbalance Parameters Sensitive to Low Back Status and, Furthermore, to the Pain Location?

We compared L5/S1 coupled moments and EMG imbalance parameters (fatigue task only) from Sample 4 (n = 20 healthy subjects, data set of session 1 only) and Sample 6 (n = 55 CLBP subjects) to assess the effect of low back status (healthy vs. CLBP). The Wilcoxon matched-pairs signed test was used for each variable (coupled moments, EMG imbalance parameters) and for each muscle pair, when appropriate.

To assess the effect of pain location, we further divided the 55 CLBP subjects into three groups, depending on the location of their pain: (1) unilateral pain on the left (n = 11), (2) unilateral pain on the right (n = 6), or pain on the midline of the back (directly on the spinal column: n = 38). None of the subjects presented pain localized bilaterally. The Kruskal-Wallis ANOVA by ranks was used for each variable (coupled moments, EMG imbalance parameters) and for each muscle pair, when appropriate, followed by the Newman-Keuls test when post hoc analyses were necessary (alpha corrected for experimentwise error rate: 0.05/6 = 0.008).

RESULTS

Question 1: What Is the Effect of Low Back Status and Force Level on L5/S1 Coupled Moments?

The healthy subjects showed a higher peak M_{ext} at L5/S1 (–251 Nm, standard deviation [SD]: 51) than CLBP subjects with unilateral pain (–210 Nm, SD: 80) and CLBP subjects with midline pain (–210 Nm, SD: 63), but the difference was not statistically significant (ANOVA: p = 0.155). Because the mass of the subjects was significantly different between the three groups (**Table 1**), we performed an analysis of covariance using mass as a covariate to account for this possible confounding effect. However, the effect of this covariate was not significant (p = 0.494) and thus had no appreciable influence on the Group main effect (p = 0.128). When producing ramp contractions without providing an M_{rot} feedback, no difference was observed between healthy and both CLBP subject subgroups (unilateral and midline pain) for the coupled moments ($|M_{lat}|$: p = 0.423 and $|M_{rot}|$: p = 0.063) across all force levels (**Figure 3(a)**). The Group × Force interaction was not significant. However, both $|M_{lat}|$ and $|M_{rot}|$ showed a significant increase across force levels (p = 0.000 in both cases). The average values of $|M_{lat}|$ and $|M_{rot}|$ reached approximately 4 to 8 Nm (depending on the group and coupled moment) at the 80 percent MVC with some subjects (three healthy and seven CLBP) peaking at values ranging from 13 to 19 Nm and two CLBP patients reaching 30 and 31 Nm.

Question 2: What Is the Effect of Visual Feedback in Axial Rotation?

The visual feedback in M_{rot} was not efficient at decreasing either the coupled moments or the EMG contralateral imbalances (statistical details in **Table 2**), except for the subgroup of CLBP subjects having a unilateral pain that significantly decreased (p = 0.011) the $|M_{rot}|$ coupled moments (**Figure 3(b)**).

For the EMG imbalance parameters, the force level influenced MF-based parameters, but none of the post hoc comparisons reached statistical significance. The most obvious force-level effects were observed for the nonnormalized |ΔRMS| parameters (**Table 2** and **Figure 4**). However, by normalizing |ΔRMS|, we completely eliminated (for MU-L5, IL-L3 and LO-L1) or reduced (for LO-T10) this effect. When only the normalized and RMS-based EMG imbalance parameters (|ΔRMS| normalized, |RMSratios|, RMS_{UI}) were considered, the significant differences always involved the 20 percent MVC force level.

Given that the normalized |ΔRMS| and |ΔMF| parameters behaved almost exactly the same way as the ratio-based parameters, according to the results related to Question 2 (**Table 2** and **Figure 4**), we decided to report

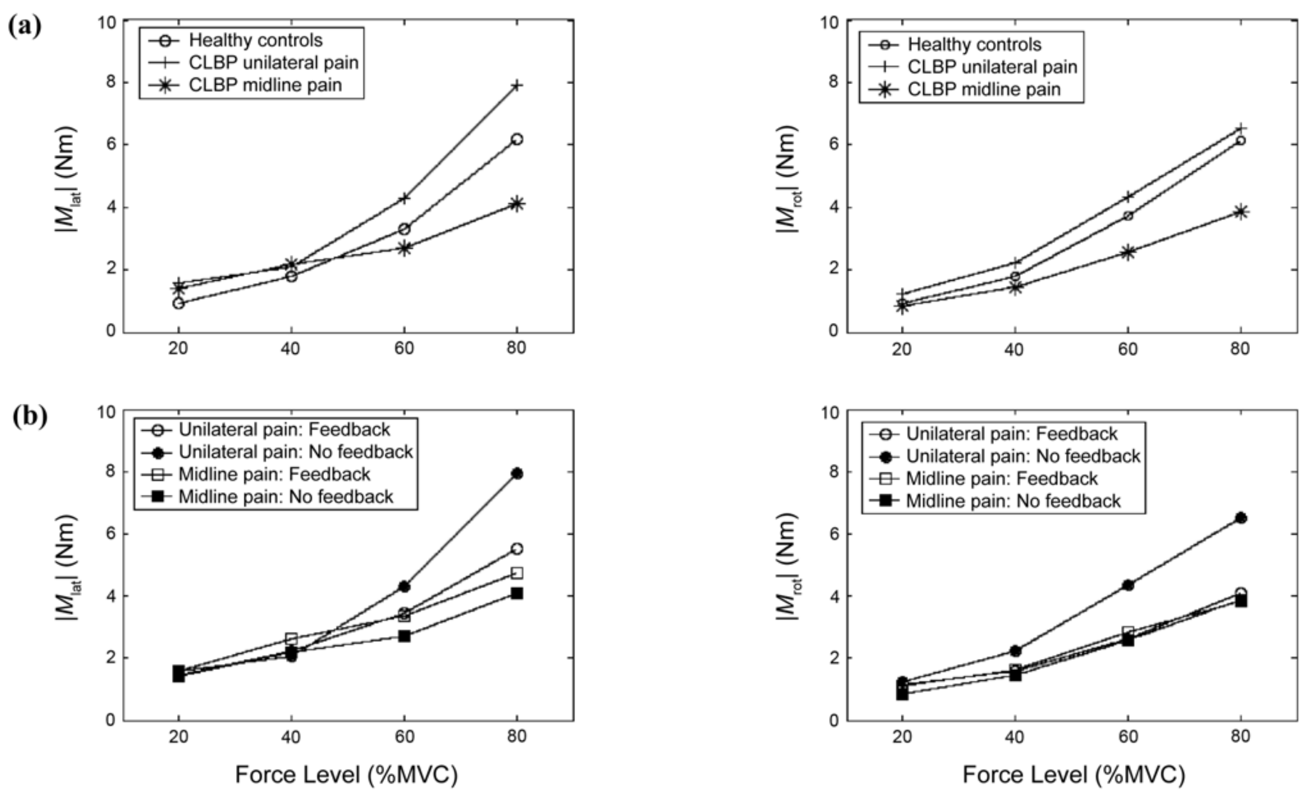

Figure 3.
Effect of **(a)** low back status and **(b)** providing visual feedback in axial rotation on coupled moments ($|M_{lat}|$ and $|M_{rot}|$) corresponding to different force levels. Standard deviations are not reported for clarity, but were generally of same magnitude (±1 Nm) as corresponding mean values. CLBP = chronic low back pain, M_{rot} = moments in extension, M_{lat} = moments in lateral bending, and MVC = maximal voluntary contraction.

Table 2.
Statistical results (*p*-values) corresponding to effect of visual feedback in axial rotation and effect of force level on different EMG imbalance parameters.

EMG Imbalance Parameter*	Effect of Feedback† (Wilcoxon)		Effect of Force Level (Friedman Test on Each Pair of Back Muscles)			
	Unilateral Pain	Midline Pain	MU-L5	IL-L3	LO-L1	LO-T10
$\lvert\Delta RMS\rvert$	0.112	0.455	0.012	0.000	0.000	0.000
$\lvert\Delta MF\rvert$	0.087	0.477	0.887	0.035‡	0.184	0.436
$\lvert\Delta RMS\rvert_{normalized}$	0.205	0.225	0.607	0.145	0.798	0.028
$\lvert\Delta MF\rvert_{normalized}$	0.077	0.986	0.578	0.026‡	0.408	0.615
$\lvert$RMSratio$\rvert$	0.615	0.224	0.630	0.081	0.430	0.023
$\lvert$MFratio$\rvert$	0.106	0.652	0.607	0.031‡	0.010‡	0.608
$\lvert RMS_{UI}\rvert$§	0.874	0.203	0.000	—	—	—
$\lvert MF_{UI}\rvert$§	0.185	0.895	0.109	—	—	—
$\lvert RMS_{CI}\rvert$§	0.359	0.075	0.053	—	—	—
$\lvert MF_{CI}\rvert$§	0.182	0.208	0.608	—	—	—

*$\lvert$EMG parameter$\rvert$ = absolute (positive) values of different electromyographic (EMG) parameters that were analyzed.
†Statistics were performed on both chronic low back pain subgroups (n = 14 with unilateral pain; n = 21 with midline pain) separately.
‡Post hoc comparisons that were not significant ($p > 0.008$).
§EMG parameters were computed from ratios of all muscle pairs, justifying why only one test (rather than four) was performed to assess effect of force level.
CI = compensated imbalance
IL-L3 = iliocostalis lumborum at L3 level
LO-L1 = longissimus at L1 level
LO-T10 = longissimus at T10
MF = median frequency
MU-L5 = multifidus at L5 level
RMS = root-mean-square
UI = uncompensated imbalance

the results of the ratio-based parameters only for Questions 3 (reliability) and 4 (sensitivity to low back status). Moreover, the reliability results (ICCs and SEMs) were also almost identical (within 5% of each other for ICC values). We included the nonnormalized $\lvert\Delta RMS\rvert$ and $\lvert\Delta MF\rvert$ parameters, on the other hand, only to stress the role played by normalization in attenuating the effect of force level (see "Discussion" for details).

Question 3: What Is the Reliability of EMG Imbalance Parameters?

Overall, the reliability scores of the different ratio-based EMG imbalance parameters ranged from poor to moderate. The only excellent ICC score (>0.75) was observed for the RMSratio of IL-L3 (ICC = 0.81) in control subjects. The percentage of the total variance explained by σ_D^2 (not shown) was always less than 6 percent, indicating that the between-days systematic error was negligible. The SEMs (expressed in percentage) for RMSratio and MFratio (values with preserved sign) were artificially inflated because the distribution of values was centered around zero.

The reliability scores (ICCs and SEMs) were quite variable, so to clearly identify the best group (control vs. CLBP) or the best EMG parameter (RMS- vs. MF-based) was impossible. However, the ICCs of RMSratio and MFratio were systematically higher than the ICCs of $\lvert$RMSratio$\rvert$ and $\lvert$MFratio$\rvert$. For the RMS-based ratios, the IL-L3 showed the best reliability results among the different muscle pairs, which was substantiated by both reliability indices (ICC and SEM). Finally, the global EMG parameters (RMS_{UI}, MF_{UI}, RMS_{CI}, MF_{CI}) were more reliable than the EMG parameters computed locally (for each muscle pair) according to the SEM values.

Question 4: What Is the Sensitivity of EMG Imbalance Parameters to Low Back Status and Pain Location?

Between-group comparisons were performed for each EMG imbalance parameter in **Table 3** (n = 20 ratio-based parameters). The comparisons between healthy controls (n = 20) and CLBP subjects (n = 55), for evaluation of the effect of low back status, revealed only two significant differences (**Figure 5**). Healthy subjects had

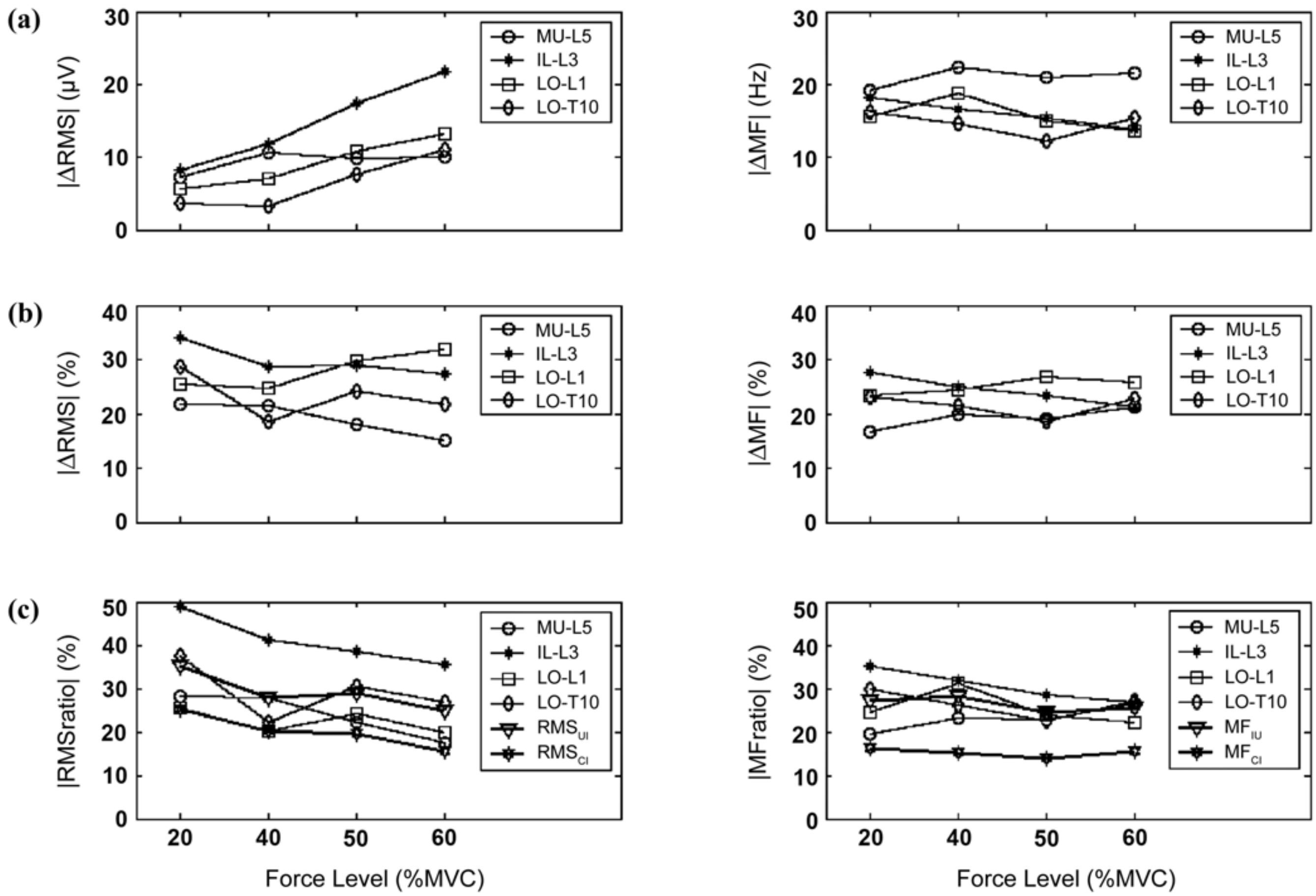

Figure 4.
Effect of force level on electromyographic imbalance parameters (positive values) corresponding to different pairs of back muscles (MU-L5 = multifidus at L5 level, IL-L3 = iliocostalis lumborum at L3, LO-L1 = longissimus at L1, LO-T10 = longissimus at T10, RMS = root-mean-square, UI = uncompensated balance, CI = compensated imbalance, MF = median frequency, and MVC = maximal voluntary contraction). Values averaged across two feedback modes (with and without moments in axial rotation) and 35 chronic low back pain subjects.

lower |RMSratio| values than CLBP subjects and higher MF_{UI} values than CLBP subjects. Interestingly, two other comparisons involving the |MFratio| parameter and showing more imbalances in healthy subjects just failed to reach statistical significance (**Figure 5**).

The comparisons between healthy subjects (n = 20) and the three subgroups of CLBP subjects (subgroups according to pain location), for evaluation of the effect of pain location, revealed no significant difference in any of the 20 ratio-based EMG imbalance parameters.

For both types of between-group comparisons (effect of low back status and effect of pain location), we also contrasted coupled moments (M_{lat}, M_{rot}, $|M_{lat}|$, $|M_{rot}|$) to ensure that each group performed the task in the same manner. Only one significant difference (effect of pain location: M_{rot}; $p = 0.034$) was observed, but the post hoc analyses were not significant.

DISCUSSION

The present study evaluated the relevance of the assessment of back muscle left-right imbalances as revealed by surface EMG. We first evaluated whether these imbalances could be the result of improper control of lumbar-coupled efforts (lateral bending and axial rotation) during an extension task (ramp contraction). However, neither low back status (Question 1) nor the presence of M_{rot} feedback (Question 2) significantly changed these coupled efforts. Likewise, providing an

M_{rot} feedback did not reduce EMG contralateral imbalances (Question 2). Next we assessed the effect of force level on L5/S1 coupled moments and different EMG imbalance parameters. Strong effects were observed, especially for coupled moments (Questions 1 and 2) and nonnormalized $|\Delta RMS|$ values (Question 2). The third issue of the study was to assess the reliability of different EMG imbalance parameters (Question 3), but the results were generally not very impressive. Finally, the fourth objective was to test the sensitivity of these EMG imbalance parameters to low back status and pain location (Question 4) but the results were inconclusive.

Table 3.
Reliability results of ratio-based electromyographic (EMG) imbalance parameters for control and chronic low back pain (CLBP) subjects.

EMG Parameter*	Muscles	Controls (n = 20)		CLBP (n = 20)	
		ICC	SEM (%)	ICC	SEM (%)
RMSratio	MU-L5	0.40	591	0.60	608
	IL-L3	0.81	102	0.68	183
	LO-L1	0.40	378	0.66	225
	LO-T10	0.45	185	0.41	239
|RMSratio|	MU-L5	0.28	68	0.34	69
	IL-L3	0.72	50	0.54	65
	LO-L1	0.00	80	0.46	74
	LO-T10	0.28	71	0.30	68
MFratio	MU-L5	0.57	145	0.32	200
	IL-L3	0.67	406	0.21	1,710
	LO-L1	0.65	5,439	0.50	374
	LO-T10	0.64	341	0.45	1,880
|MFratio|	MU-L5	0.33	77	0.18	88
	IL-L3	0.49	71	0.21	65
	LO-L1	0.48	59	0.27	71
	LO-T10	0.26	63	0.23	82
RMS_{UI}	—	0.43	40	0.57	33
MF_{UI}	—	0.53	35	0.38	33
RMS_{CI}	—	0.59	306	0.68	397
MF_{CI}	—	0.59	3,002	0.21	775

*Each EMG parameter was treated using its original sign (e.g., RMSratio) or using its absolute or positive counterpart (e.g., |RMSratio|). Uncompensated imbalance (UI) parameters always give positive values by definition. Compensated imbalance (CI) parameters were always treated with their original sign.
ICC = intraclass correlation coefficient
IL-L3 = iliocostalis lumborum at L3 level
LO-L1 and LO-T10 = longissimus at L1 and T10 levels
MF = median frequency
MU-L5 = multifidus at L5 level
RMS = root-mean-square
SEM = standard error of measurement

Some limitations of the present study may impair the generalizability of the present result. The results concerning the assessment of force level or the effect of providing an M_{rot} feedback were generated from a ramp contraction, which might not be entirely comparable to sustained contractions at a given relative force level. Ramp contractions are more difficult to perform and probably provide less stable efforts, but the stationarity of EMG signals is acceptable during such contractions, at least for upper-limb muscles [30]. Moreover, the EMG imbalance parameters extracted from the ramp contractions were calculated from only one RMS or MF value at each force level. This procedure probably produced less stable EMG parameters than during the fatigue task in which the average of several values was calculated, as proposed by Oddsson and De Luca [22], and in which the stationarity of the EMG signals was probably more adequately respected. Therefore, comparisons of our ramp results (effect of force level) with Oddsson and De Luca [22], who used a fatigue task, must be made with caution. However, this should not affect the comparisons between the nonnormalized and normalized EMG imbalance parameters.

Possibly, the CLBP subjects were not impaired enough to show changes in EMG contralateral imbalances

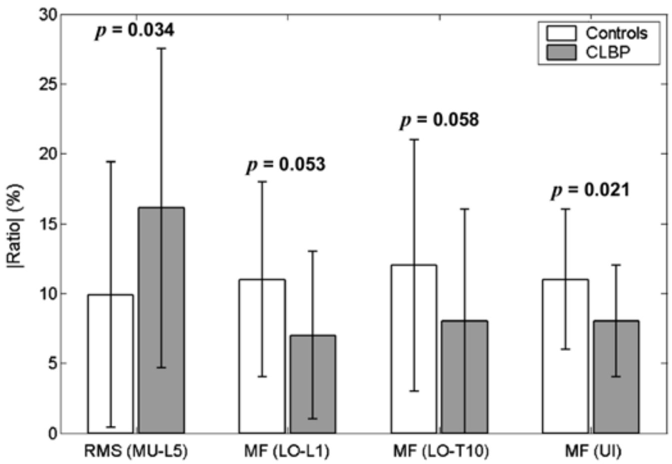

Figure 5.
Electromyographic imbalance parameters that showed, for some muscles, statistically significant or almost significant differences between healthy controls (n = 20) and chronic low back pain (CLBP) subjects (n = 55). Error bars represent standard deviations.

or in the production of coupled efforts. The present CLBP subjects were at work at the time of testing, reported a relatively low pain intensity score, and showed minimal disability according to a gradation proposed previously for the Oswestry questionnaire [26]. Moreover, EMG contralateral imbalances are not expected to occur in all CLBP subjects, so to obtain statistically significant differences between groups (healthy vs. CLBP) is difficult, even when the location of pain is considered. Another limitation is that some factors that may influence EMG contralateral imbalances were not accounted for because CLBP subjects with potentially significant leg length discrepancy were not excluded and the possible effect of handedness [18] was not assessed because only 5 of the 55 CLBP subjects were left-handed. However, a systematic effect of handedness would have produced EMG contralateral imbalances with a clear positive or negative sign, which was not the case in the present right-handed dominant sample of subjects. Finally, M_{rot} errors can reach 8.8 Nm at 80 percent MVC because of lateral misalignment of the subject in the dynamometer [20]. Consequently, some variability might have been introduced into the EMG imbalance parameters for subjects who could have produced perfect sagittal efforts (no coupled moments) but, because of misalignment in the dynamometer resulting in an erroneous M_{rot} visual feedback, exerted an opposing M_{rot} to compensate for this error.

Questions 1 and 2: Are EMG Contralateral Imbalances Affected By an Inadequate Control of Asymmetric Efforts?

CLBP subjects (two subgroups: 14 unilateral pain and 21 midline pain) did not generate higher coupled moments than healthy controls, even at high force levels where pain exacerbation could have played a role (Question 1). These findings were contrary to our expectations because CLBP subjects were expected to produce such asymmetric efforts to avoid pain exacerbation, especially if the pain was located unilaterally. On the other hand, providing an M_{rot} feedback reduced the M_{rot} in the subgroup of CLBP subjects with unilateral pain (Question 2). However, the difference (2.4 Nm at 80% MVC) was marginal and probably without any physiological significance. This contention is further supported by the absence of Feedback effect in the corresponding EMG imbalance parameters (Question 2). However, providing the M_{lat} feedback in an effective manner (in addition to the M_{rot} feedback but without interfering with the extension task) may still help reduce the coupled moments and EMG contralateral imbalances.

These findings suggest that the control of coupled efforts with the use of visual feedback was no more important for CLBP than for healthy subjects. However, this finding does not mean that the control of these asymmetric efforts is unnecessary. Our opinion is that providing a feedback of coupled efforts is necessary because some subjects exhibit large asymmetric efforts. For example, the reviewing of the M_{rot} results corresponding to the 80 percent MVC force level revealed that 3 out of the 35 CLBP subjects generated relatively large M_{rot} without feedback (range: 15 to 19 Nm). Our providing M_{rot} feedback allowed them to reduce these values considerably (range: 4 to 9 Nm). Interestingly, the RMS_{CI} decreased concomitantly with the decrease in M_{rot} (range of values without feedback: 17% to 26%; with feedback: 6% to 18%), supporting the view that part of the EMG imbalances might be attributable to a lack of control of coupled moments.

Question 2: Are EMG Imbalance Parameters Affected By Force Level?

The MF-based EMG imbalance parameters were relatively insensitive to the force level (**Figure 4**). On the other hand, the nonnormalized $|\Delta RMS|$ parameters heavily depended on this factor, demonstrating that the difference in EMG activation between contralateral back muscles increases with force. This increase is probably explained by the concomitant increase in the coupled moments, as substantiated in the present study. The low back status or pain location cannot explain this phenomenon because no group difference was obtained relative to coupled moments at any force level (Question 1). These results imply that to compare the EMG imbalance between different individuals, one would need to standardize the level of effort at a given percentage of MVC. However, the determination of MVC is problematic for CLBP subjects because they are reluctant to produce true maximal efforts. Such a behavior would add a significant amount of variability to the corresponding nonnormalized EMG imbalance parameters. Fortunately, the normalized RMS-based parameters ($|\Delta RMS|$ normalized, $|RMSratio|$, RMS_{UI}) were almost free of the influence of force level. In fact, the few significant differences always involved the 20 percent MVC force level (never between the 40%, 60%, and 80% MVC force levels). In other words, these results showed that normalized EMG imbalance parameters remain relatively constant between the 40 and 80 percent MVC tasks during a ramp contraction. This "attractive property" of the normalized RMS-based parameters has been previously observed in ratio-based parameters for healthy subjects during an 80 percent MVC fatigue task lasting 30 s [22]. According to the present results, if these EMG imbalance parameters have a comparable behavior during a ramp contraction and a steady contraction (fatigue task), the results obtained by Oddsson and De Luca [22] obtained from a steady contraction can now be extended to CLBP subjects. For example, if the task is to sustain a contraction at 80 percent MVC and if CLBP patients were to produce a "true" force level larger than 40 percent MVC, then normalized EMG parameters could be produced for comparison with healthy subjects.

Question 3: Are EMG Imbalance Parameters Reliable?

The poor-to-moderate reliability of EMG imbalance parameters suggests that if EMG imbalances truly reflect back muscle impairments, sources of error impair its clinical use. These results concur with previous findings related to MF-based EMG parameters sensitive to left-right differences [23–25]. We performed additional analyses (not reported here) on each EMG imbalance parameter in **Table 3** to evaluate whether between-group comparisons (20 healthy vs. 20 CLBP subjects) would at least be reproducible from day to day (day 1 vs. day 2 vs. day 3). The corresponding results (*p*-values) showed that even this gross appraisal of reliability led to inconsistent results in many EMG imbalance parameters, with *p*-values ranging from significance ($p < 0.05$) to values beyond 0.70 in the worst cases ($|RMSratio|$ of LO-T10, MF_{UI}, and MF_{CI}).

To our knowledge, reliability results corresponding to RMS-based parameters are unique but, unfortunately, do not show better reliability scores than MF-based parameters. The best reliability results were observed for the RMS-based EMG imbalance ratios of the IL-L3 muscle. This might be explained by the fact that this muscle is more laterally located from the midline and, consequently, has mechanical advantage (longer lever arm) to produce asymmetric efforts in a reproducible manner.

The ICCs of RMSratio and MFratio were systematically better than those of $|RMSratio|$ and $|MFratio|$. This might be partly attributable to the higher intersubject variability of RMSratio and MFratio values, which could have helped obtain higher correlation results (ICC). We are tempted to speculate that these results support the view that the sign or direction of the EMG imbalance (left < right or left > right) was attributable to a physiological mechanism related to pain or to an asymmetry in muscle fiber composition. However, inconclusive results related to Question 4 (sensitivity to low back status and pain location) do not support this hypothesis.

Can these reliability results be improved? We observed from the low proportion of the total variance attributed to between-day variations (<6% in all cases) that these errors were mainly random. In such a situation, the only way one could improve reliability would be to better standardize the measurement protocol and/or to average the values from several measurements. With regard to the standardization of the measurement protocol, the possibility of efficiently controlling all the coupled moments (M_{lat}, in addition to M_{rot}) would be of interest. In addition, the use of a template to reposition the surface electrodes from day to day could also be an important improvement. With regard to the averaging of measurements, the most popular solution is to perform several trials. However, the use of a relatively long-lasting contraction to compute relatively stable estimates of EMG imbalance induces muscle fatigue, thus limiting the use of such a strategy unless sufficient recovery is allowed between contractions [31]. Usually, the averaging of EMG parameters across muscles increases the reliability of the new composite variable [23]. However, this was not the case here, according to the reliability results of the

RMS_{UI} and MF_{UI} parameters. To summarize, we find that obtaining better reliability scores for EMG imbalance parameters might be difficult, but still possible.

Question 4: Are EMG Imbalance Parameters Sensitive to Low Back Status and Pain Location?

Some EMG imbalance parameters (RMS- and MF-based), depending on the back muscle pair, were sensitive to low back status. RMS-based ratio parameters are designed for measuring the level of asymmetry in the activation of contralateral muscles, while MF-based ratio parameters are thought to be for measuring imbalances with regard to muscle composition [22]. However, contrary to Oddsson and De Luca [22], MF-based ratio parameters showed lower values in CLBP subjects than in healthy controls, a rather counterintuitive finding. Nevertheless, one must recognize that even if this situation occurred three times (**Figure 5**), statistical significance was reached only once.

The fact that the significant differences between healthy and CLBP subjects occurred only when the absolute (positive) values of the ratio parameters were used was not surprising because using absolute values avoids the cancellation of EMG imbalance ratios with a different sign. An interesting question would be to ask whether the sign of these ratios (direction of imbalance) is linked to a physiological mechanism associated with low back pain. However, in the present study, EMG imbalance parameters were shown to be insensitive to pain location. This issue has been studied by Oddsson and De Luca but no statistical analyses were provided [22]. However, looking at the distribution of ratio values in Figure 6 of their paper [22], we find that nonsignificant differences may result if RMS-based or MF-based ratios were tested individually. In the present study, the small samples of CLBP subjects with clear unilateral pain (n = 11 with left pain and n = 6 with right pain) involved in this analysis may have possibly impaired the statistical power, especially with the use of unreliable EMG parameters. However, our point of view is that if clear and clinically relevant differences were present between healthy and CLBP subjects, these differences would have produced statistically significant results, at least for the subgroup of left unilateral pain (n = 11). Thus, considering the few statistically significant results and the counterintuitive findings, we conclude that EMG imbalance parameters were not sensitive to CLBP, at least for the CLBP subjects in the present study who were not severely impaired.

CONCLUSIONS

The current study provided limited evidence that EMG contralateral imbalances were related to the lack of control of asymmetric efforts. Furthermore, the asymmetric efforts were apparently not related to pain reporting. A more efficient control of M_{lat} in addition to M_{rot} might be necessary for the reduction of EMG contralateral imbalances. The assessment of the effect of force level revealed that EMG imbalance parameters must be normalized to be independent of the force level. In fact, normalized EMG imbalance parameters remain relatively constant between 40 and 80 percent MVC. This finding has strong clinical relevance when clinicians and researchers use these EMG imbalance parameters to assess CLBP patients. The reliability of EMG imbalance parameters was moderate at best. Consequently, more research is needed to improve this reproducibility before such an assessment protocol in clinical practice is used. Finally, EMG imbalance parameters were not shown to be sensitive to CLBP or to pain location. However, such an EMG assessment, when applied to more severely affected CLBP subjects or to subjects with more defined unilateral pain than in the present study, may be able to give more encouraging results.

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