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Gait analysis in idiopathic scoliosis before and after surgery: a comparison of the pre- and postoperative muscle activation pattern

Received: 5 May 1997
Revised: 21 August 1997
Accepted: 29 August 1997

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Abstract In a prospective experimental study the level gait activity scores of the iliocostalis lumborum, gluteus medius, tensor fasciae latae, vastus lateralis and peroneus longus muscles of both body sides were examined by computerized electromyography in 23 patients with idiopathic scoliosis before and after CD instrumentation. The pre- and postoperative findings were examined as to asymmetric patterns in muscle requisition during gait and the respective changes induced by the spinal correction. These results were compared with the corresponding results obtained in healthy subjects in two independent sessions with identical experimental conditions. A muscle activity asymmetry coefficient was defined to quantify the degree of left/right muscle activation asymmetry observed. Postoperatively a statistically significant reduction ($P <$

0.05) of a preoperatively strongly increased activity was found in the lumbar muscles of the convex side of double major scolioses as well as in the gluteus medius and tensor fasciae latae muscles of the concave side of thoracic curvatures. Both the casuistic and statistical analysis of the results of our study support the hypothesis that activity asymmetries observed in the paravertebral musculature in idiopathic scoliosis patients are the result of the scoliotic body deformities, with consequent asymmetries in the biomechanical force patterns of body postures and body motions, rather than an aetiological factor of scoliotic curvatures.

Key words Electromyography · Orthopaedic surgery · Idiopathic scoliosis · Gait analysis · Spinal correction

Introduction

The role of changes observed in the muscle activation pattern of scoliotic patients in typical body postures and body motions has been an issue for some decades now. Deviations from the pattern observed in healthy subjects have been discussed in the context of both the aetiology and the biomechanical effects of this disease. The first electromyographic (EMG) investigations of the long erector spinae muscles were reported by Lericque and Le Coeur in the year 1951 [17]. Bayer [2, 3] published the results of

EMG measurements in some 100 scoliotic patients. According to his findings the EMG activity of the extending muscles of the back was higher on the convex side of the curvature in 80% of the examined patient group. Similar results were published both by Allenbach and Wiest [1] and Riddle and Roaf [22]. In this context, Gruca [12] proposed the idea of an asymmetric muscle paralysis as an aetiological factor of scolioses. A predominant EMG activity of the erector muscles on the convex side of the curvature was also observed by Brussatis [10]. According to his interpretation, this effect is a biomechanically necessary result of the scoliotic curvature of the spine rather than its

cause. The moment arm of the erector spinae muscle system is shorter on the convex side of the deformed back, thus requiring respectively higher muscle forces to stabilize the upright posture of the upper body. Henssge [17] carried out EMG measurements in two groups of 60 scoliotic children each, with the disease being idiopathic in one group and congenital or following poliomyelitis in the other. Increased denervation potentials were found in both patient groups. The author further proposed that an asymmetric activity in the erector trunci muscle system might be a symptom indicating a progressive type of scoliosis. Güth et al. [13] observed in scoliotic patients wearing a Milwaukee brace that the EMG activity of the erector muscles increased on the convex side when walking without the brace. Güth and co-workers [14] found both in static and dynamic EMG measurements a distinct asymmetric activity in non-progressive scolioses too. Güth also found that the activity of the convex erector muscles in the thoracic region increased in proportion to the degree of lateral displacement of the upper body to the convex side (private communication). He concluded from these observations that the activity of the erector spinae muscle system is always altered so as to act against a progression of the curvature. The asymmetry thus measured is a consequence of a decreased activity on the concave side rather than of an increased activity on the convex side. He also stated that a disturbed muscle activation pattern in the lower extremities in gait may give rise to a generally enhanced muscle force pattern in the upper body. Since a given spine curvature is more easily increased than decreased by additional muscle forces both under static and dynamic conditions, a poorly coordinated walking pattern may thus promote the progression of a scoliosis. Other authors also described muscle imbalances in scoliosis [22].

An operative correction of a scoliotic curvature may bring about conditions in the upper body that are, at least in some biomechanical aspects, close to normal. The question arises in this context of to what extent this new situation affects a preoperatively observed aberrant muscular activation pattern in gait. In order to get some insight into this problem, we carried out prospective EMG investigations in scoliotic patients before and after spinal correction surgery using CD instrumentation.

Materials and methods

The electromyographic gait analysis system

Our investigation was carried out with the gait analysis system developed in the biomechanics laboratory of our department, which has been described in more detail elsewhere [6–8, 19, 20]. Comparing the EMG activity of a muscle under different experimental conditions (or, for instance, pre- and postoperatively, as in our investigation) is not a straightforward task, as the raw EMG signal is superimposed by considerable stochastic fluctuations, even at constant muscle force. Although higher muscle force usually yields

higher mean EMG amplitudes, it may be difficult to quantify such an increase for comparative studies. Some problems involved here concern the dependence of the EMG signal amplitude at constant force on the muscle state, speed and direction of contraction, and its state of training and fatigue. In comparing EMG amplitudes of a muscle pre- and postoperatively, comparable experimental conditions have to be provided in the first place. Moreover, EMG signals that closely correspond to a mechanical muscle action in a quantitative manner can only be obtained by suitable averaging methods. In quasistatic body statures this implies averaging of the rectified signal over a suitably long period of time. The result obtained is a number that may be calibrated to correspond, within certain limits, to the static muscle force [4, 9, 19]. EMG signals picked up in body motions are more difficult to process. In fact only a motion pattern that can be cyclically repeated a sufficient number of times offers a possibility of deriving from the raw EMG signal a myoelectric activation curve that is typical for the action of the investigated muscle and that can be reproduced within narrow limits. The raw EMG signals of all motion cycles have to be low-pass filtered, rectified, compressed to one standard length, and averaged by additive superimposition for this purpose.

An EMG activity curve thus obtained from an appropriately high number of repeated motion cycles is highly reproducible at unaltered experimental conditions and typical for the mechanical muscle action in the course of the body movement. Its amplitude does not, however, necessarily coincide with the muscle force amplitude, as the correspondence of muscle force and EMG is influenced by parameters like state, speed and direction of muscle contraction, which change throughout the motion cycle. This has to be kept in mind when trying to interpret and compare curves obtained from such EMG signal averaging.

In our laboratory the patient carries out ten test gaits of about 15 m length each on a level walkway. In the present study we investigated the EMG activity of the iliocostalis lumborum, the gluteus medius, the tensor fasciae latae, the vastus lateralis and the peroneus longus muscles of both sides. The EMG signals of the investigated muscles are picked up by surface electrodes and pre-amplified and prefiltered in a miniature signal-conditioning box fixed to the patient's body. The angular motions of the upper and the lower leg in the sagittal plane are measured by the optoelectronic goniometer system Polgon [23]. The EMG and angular motion signals are transmitted to a computerized signal recording and processing unit via a trailing cable running along an overhead rail. In the data analysis the angular motion recorded is used to identify the motion cycles (full strides) of the test gait sequences. We thus generate for every muscle investigated a set of 50 EMG activity curves that correspond to biomechanically comparable motion patterns. To prepare these curves for the subsequent averaging, they are linearly compressed to the temporal length of the shortest full stride recorded. A suitable digital low-pass filtering and a full-wave rectification of the curves is then carried out. The subsequent averaging of this preprocessed ensemble of raw EMG curves, which correspond to the biomechanically comparable muscle action patterns of the recorded gait cycles, yields a smooth activity curve that is highly characteristic for every muscle and can be reproduced in a test subject within narrow limits if the experimental conditions remain unchanged. If a change in experimental conditions produces any noticeable effect on the biomechanical muscle action in gait this will alter the EMG averages. We thus conclude that if an increase or decrease of the averaged EMG amplitude at some phase of the gait cycle is measured this is due to a respective increase or decrease of muscle force, but without a strictly defined quantitative relationship. In the context of our study, a change in experimental conditions may be due to changes in either the walking environment conditions or in the test subject's body. As the walking environment is kept unchanged in all measurements, we conclude that any EMG changes observed are due to changes in the test subject's locomotive system as a result of the spinal correction surgery.

Fig. 1 Electromyographic (EMG) activity curves of a healthy subject in a level test walk. The curves were obtained from the raw EMG signals of a set of 50 full strides by full-wave rectification, low-pass filtering, and ensemble averaging. The upper left and right columns show the activities of some selected muscles of the left and right body side in a first experimental session. The lower columns show the respective results obtained in a second examination carried out 4 weeks later under identical experimental conditions. The horizontal time axis corresponds to one gait motion cycle. Its beginning ($t = 0$) and ending ($t = T$) coincides with the vertical position of the left lower leg in its forward motion during its swing phase. The vertical axes of all graphs are scaled in the same arbitrary units (*lumbar* iliocostalis lumborum, *glut. med.* glutaemus medius, *tensor* tensor fasciae latae, *vast. lat.* vastus lateralis, *peroneus* peroneus longus)

In Fig. 1 typical EMG activity curves of a healthy subject obtained in a test walk as obtained by the signal processing described above are demonstrated. The upper left and right columns show the activities of some selected muscles of the left and right body side in a first experimental session. The lower columns show the respective results obtained in a second examination carried out 4 weeks later under identical experimental conditions. The horizon-

Fig. 2 Correction of the thoracic and double major curves by location of the scoliosis

tal time axis corresponds to one gait motion cycle. Its beginning ($t = 0$) and ending ($t = T$) coincides with the vertical position of the left lower leg in its forward motion during the swing phase. The degree of left/right symmetry in the EMG activities of the investigated muscles as well as of their reproducibility in different experimental sessions is clearly visible. Only the peroneus longus muscle activities show a rather high variation. This reflects a relatively high freedom of the test subject in the muscular control of his foot rolling on the floor.

Characteristics of the patient and control groups

The group of patients examined pre- and postoperatively with our motion analysis system included 23 (3 male and 20 female) patients suffering from idiopathic scoliosis and 1 female patient suffering from congenital scoliosis. The scolioses were classified as thoracic in 16 patients and as double major curve in 6. In one female patient suffering from lumbar scoliosis the full investigation could not be performed for technical reasons. The gait analyses were carried out immediately before and 6–9 months after a posterior fusion employing the CD instrumentation. Age at surgery ranged from 11.3 to 29.3 years. The average preoperative Cobb angle [11] was 58.4° preoperatively and 20.8° postoperatively. The CD surgery thus effected an average reduction of 37.6°, or 59.6%.

Considering the thoracic scolioses separately, there was an average preoperative Cobb angle of 61.9°, which was reduced to an average of 25.0°, corresponding to a mean correction of 36.9° or 59.6%. In the thoracic curves of the double major scolioses there was a preoperative average Cobb angle of 53.0°, which was reduced to an average of 15.3°, corresponding to an average correction of 37.7° or 71.1%. In the respective lumbar curves we found an average preoperative Cobb angle of 54.0° being reduced to an average of 14.3°, corresponding to an average correction of 39.7° or 73.5% (Fig. 2).

Control gait analyses with identical experimental conditions were carried out in four male and four female healthy test subjects. The average age of this group was 20.7 years, ranging from 13.8 to 34.0 years. To test the stability of an individual EMG activity pattern in standardized level gait each test subject was examined twice at an interval of about 2–4 weeks. A typical result of the EMG investigation of a healthy subject is shown in Fig. 1.

Fig. 3 Preoperative (*upper columns*) and postoperative (*lower columns*) EMG activity curves of a 12-year-old girl suffering from an 88° right thoracic curve that diminished to 35° postoperatively

Results

Figures 3 and 4 (single and double major curves) show examples of results obtained in the patient groups. In their qualitative aspects these findings are representative of the majority of the patients examined.

Figure 3 shows the EMG status of a 12-year-old girl suffering from an 88° right thoracic curve that was reduced to 35° postoperatively. Preoperatively there is clearly increased activity of the femoral abductors (glutaeus medius and tensor fasciae latae muscles) of the left (concave) side, reflecting the asymmetric biomechanical conditions induced by the scoliotic curvature in the frontal plane. In the stand phase of the left leg the ipsilateral

Fig. 4 Preoperative (*upper columns*) and postoperative (*lower columns*) EMG activity curves of a 12-year-old girl suffering from a double major scoliosis. The basic pre/postoperative characteristics are rather similar to those of Fig. 3, but on the reverse body side (the postoperative curve of the vastus lateralis muscle is missing here due to a failure of the EMG channel in that measurement)

femoral abductors have to balance in the hip joint an increased pelvic moment engendered by a shift of the thoracic mass towards the right body side. The lumbar muscles are activated twice within one gait cycle, the respective EMG activity peaks coinciding with the beginning of the stance phases of the left and right leg, respectively. There is heavily increased activity of the muscles on the convex side of the scoliotic curve reflecting the disturbed static conditions in the upper body. Postoperatively the biomechanical asymmetry in the upper body diminished considerably, with a consequently diminished asymmetry of the pertaining muscular activities. In contrast, no such characteristic asymmetries are found in the activities of

the knee extensors (vastus lateralis muscle) and foot stance muscles (peroneus longus muscle). The postoperatively diminished activities of both vastus lateralis muscles is a consequence of the new biomechanical status without showing specific effects on a particular body side. This case study provides further evidence against the theory that inherent asymmetries in the muscle activities of the right and left body sides may be an origin of idiopathic progressive scoliosis. The reduction of muscle activity asymmetries observed after operative correction of scoliotic biomechanical asymmetries proves that the scoliosis was the origin rather than the result of a disturbed muscle activation pattern. This is also clearly shown by the case studies presented in Figs. 3 and 4.

Figure 4 shows the result obtained in a 12-year-old girl suffering from a double major scoliosis. The basic pre/postoperative characteristics are rather similar to those in Fig. 3 except on the opposite body side (the postoperative curve of the vastus lateralis muscle is missing here due to a failure of the respective EMG channel in the respective measurement). There are a clear reduction and symmetrization of the preoperatively distinctly asymmetric activities of the lumbar muscles as well as of the hip muscles.

Statistical considerations

Due to the complexity of the EMG activity patterns in their individual detail in different subjects it is difficult to define biomechanically relevant parameters that readily lend themselves to statistical analysis. One possible statistical approach is the definition of an individual muscle activity asymmetry coefficient (MAAC). To this end we compute, in a final EMG data processing step, the integral activity A of the averaged EMG curves over the full gait cycle. Although not describing the pre/postoperative muscle activity changes in functional detail, this quantitative value is suitable for a global description of muscular activity shifts from one body side to the other.

Denoting by A_r the integral EMG activity of a muscle of the right body side and by A_l that of its left counterpart, we define the MAAC for this muscle pair as follows:

$$\text{MAAC} = (A_r - A_l) / (A_r + A_l)$$

It follows from this definition that $\text{MAAC} = 0$ for perfectly symmetric conditions ($A_r = A_l$). A right- or left-hand muscle activation surplus yields a positive or negative MAAC, respectively, with $\text{MAAC} = +1$ for a complete right-hand ($A_l = 0$) and $\text{MAAC} = -1$ for a complete left-hand ($A_r = 0$) asymmetry.

Using the Wilcoxon pair difference test and the Mann Whitney U-test the following statistical studies were carried out.

Comparison of asymmetries in patients and controls

The EMG muscle activities measured in the control group of healthy test subjects were not completely symmetric either. This may result in part from an electrical asymmetry in the EMG signal pick-up and in part from an actual asymmetry in muscle forces. We thus compared the group averages of the MAAC found in the pre- and postoperative patients with those found in the healthy test subjects.

In the preoperative thoracic scoliosis group, only for the tensor fasciae lata muscles was the MAAC significantly higher ($P < 0.05$) than in the control group. Postoperatively there was no longer a statistically significant difference. In the preoperative double major curve group only for the iliocostalis lumborum muscles was the MAAC significantly higher ($P < 0.04$) than in the control group. Postoperatively there was no longer a statistically significant difference.

Comparison of MAAC changes in patients and controls

The MAACs measured in the control group of healthy test subjects were not completely identical in experimental sessions carried out on different days. This may result in part from changes in the force/EMG relationship in the muscles and in part from biomechanical changes in the gait pattern of the subjects. We thus compared the changes of the group averages of the MAAC found in the patient groups from the pre- to the postoperative measurements with the corresponding changes found in the healthy test subjects from the first to an independent second session with identical experimental conditions.

In the thoracic scoliosis group, the MAAC change was significantly higher ($P < 0.04$) than in the control group only for the gluteus medius muscles. In the double major curve group, the MAAC change was significantly higher ($P < 0.05$) than in the control group only for the iliocostalis lumborum muscles.

In the control group no such statistically significant changes were observed in any investigated muscle pair. These statistical results demonstrate that the asymmetries in muscular activity observed in the patients and their postoperative changes are specific for the underlying spinal disorder and its operative correction in a few of the investigated muscles only. This does of course not mean that dramatic muscle asymmetries observed in some other muscles of some individual patients as well as their postoperative activity symmetrization are coincidental.

Discussion

The results of our investigation confirm both in an extended and in a more quantitative manner the asymmetrical activation of the paravertebral muscles as found by

other authors [10, 13, 18] with different EMG methods. There is a remarkable postoperative symmetrization of the activity of the iliocostalis lumborum muscles in most of the double major curve patients. In the thoracic curve patients this effect is also observed in the hip muscles investigated. No similar effects could be observed in the investigated muscles of the upper and lower leg that are not directly affected by an asymmetric mass distribution in the upper body. This is another piece of evidence in support of the hypothesis that deviations from regular muscle activation observed in scoliosis patients are of a biomechanical rather than a general systemic origin. The preoperatively observed asymmetry in muscle activation is thus a result of an asymmetric geometry of the upper body with a consequent asymmetric muscle force pattern. Restoring in large part the geometric symmetry of the body engenders a corresponding symmetrization of the pertaining muscle forces.

Among the examined patients there was one girl suffering from a congenital scoliosis. The pre- and postoperative EMG activities found in this case were quite similar to those found in the idiopathic scolioses. This is in keeping with the results obtained by other authors [16] with different methods. The widely restored symmetry of the muscular activities in level walk following surgery show that the effects brought about by an adequate corrective surgery of a scoliotic spine are not only of a cosmetic nature, but of a most favourable biomechanical nature as well. The level walk being one of the most ubiquitous events in everyday life, a restored regular muscle activation pattern in this body motion may prevent biomechanically unfavourable long-term effects not only in the signal region but in the muscles and joints of the hip as well.

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