ANALYSIS OF THE QUADRICEPS MUSCLES CONTROL STRATEGY IN THE ANTERIOR KNEE PAIN

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Abstract.
Anterior Knee Pain (AKP), elsewhere called patello-femoral pain, is a common pathological condition, particularly for young people and athletes. In this pathology the more common problem is the abnormal motion of the patella during knee bending. It could depend on muscular or structural imbalance. Usually, the rehabilitative therapy consists of a conservative treatment of the AKP based on the strengthening of the Vastus Medialis. The aim of this article is to study the modification of the muscle control strategy in AKP patients. The analysis of the strategy of muscle activation is important for an objective measurement of the knee functionality as far as it helps in diagnosis and in monitoring the rehabilitative treatment. Surface Electromyography (EMG) from the three superficial muscles of the Femoral Quadriceps during a concentric isokinetic exercise has been analysed. To describe these modifications the Linear Envelope (LE) decomposition proposed by Chen and Shavi [8] has been used. Significant modification of the activity of the Vastus Medialis respect to other quadriceps muscle has been recognised in AKP patients. Such muscular unbalance results in abnormal motion of the patella.

Key words: Anterior Knee Pain, EMG, isokinetic

1. INTRODUCTION
Anterior Knee Pain (AKP), elsewhere called patello-femoral pain, is a very common pathological condition. Many people complain about pain located near the patella when walking down stairs, keeping the knee bent for long periods or applying pressure on the patella. Such pathological condition is particularly common in young people and in athletes as well [1][2][3].
The origin of the AKP is not fully clear yet. Its causes may be either bio-mechanical or bio-chemical. The more common problem is the abnormality in the way the patella moves when the knee is bent or straightened. This could depend on a muscular or a structural imbalance [4].
Many studies on the subject reported that the quadriceps wasting and weakness are the most constant symptoms of patello-femoral disorders [5]. The strengthening of the Vastus Medialis usually diminishes or completely relieves the AKP symptoms, but the mechanism of its action is not clear yet. Generally, the assessment of the progress is based on subjective parameters relate to pain and dysfunction. However, at the present the increasing availability of isokinetic devices in the rehabilitation environment allows therapists to test the mechanical activity of the quadriceps muscles.
To study the dynamic misalignment of the patella, occurring mainly in the coronal plane, is important to investigate, during the extension, the relationship among the activity of the individual quadriceps muscles and their synergy. The EMG LE represents a simple but efficient method to collect information about single muscle activity during isokinetic concentric exercise [6]. A previous study [7] demonstrated that the Linear Envelope (LE) of the electromyogram (EMG) follows the variations of the muscle activation and matches the produced torque in isometric contraction. However, the raw EMG LE is too complex to be utilised in a synergy analysis. More concise information could be considered. The classical on-off pattern gives information only about the start and the end of the muscle activity but not on its amplitude. To overcome this limitation, in this work the EMG LE was decomposed into a series of activation phases, in term of gaussian pulses as proposed by Chen et al. [8].
The aim of this paper is to study the modification of the muscle control strategy in healthy subjects and AKP patients recording the EMG from the three superficial muscles of the femoral quadriceps during a concentric isokinetic exercise.

2. METHODS AND MATERIALS
2.1 Subjects - Myoelectric and biomechanical signals of 30 healthy subjects (male, aged 18-38, 30 ± 6.2) (30 for the right leg, 30 for the left leg) and signals of 12 pathological subjects (male, aged 20-36, 29 ± 5.6) suffering from Anterior Knee Pain, have been analysed. All the patients have been examined by experienced orthopaedic surgeons (at the Orthopaedic Department of Medicine and Surgery, University of Naples “Federico II”); their diagnosis was based on clinical signs.
2.2 Testing equipment - The LIDO ACTIVE isokinetic equipment, by Loredan, was used to measure knee extension and torque within the range of motion 0°-90° degree of extension in concentric mode at a velocity of 90°/s. The patients sat in an ergonomic adjustable seat with the tight and the back supported. He is fastened to the seat by a seatbelt placed above the pelvis. The centre of the motion of the lever arm was manually aligned as well as possible with the flexion-extension axis of the knee joint, and the resistance pad was placed on the distal part of tibia. Equipment automatically corrects the torque value for the gravitational force.

2.3 Measurement protocol - The measurement protocol includes first a limbering up and familiarisation with the isokinetic equipment then a cycle of 15 knee flexion-exentions at 90°/s velocity. The myoelectric signal was recorded using Ag/Ag-Cl electrodes (disc biopotential electrodes with a diameter of 0.9 cm) in bipolar arrangement with a 20 mm inter-electrodic distance. The EMG signals from the three superficial muscles of the quadriceps: Vastus Lateralis (VL), Rectus Femoris (RF), Vastus Medialis (VM) were recorded simultaneously with the signals of position and torque from the isokinetic equipment.

2.4 Data acquisition and display - The EMG signals, relative to VL, RF and VM, are collected, amplified and filtered by three differential amplifiers for biopotentials (8811A, Hewlett-Packard, Massachusetts, USA). The bandwidth was set to 5 Hz-1000 Hz, with a signal gain of 1000 V/V. Knee torque and position measurements are provided directly by the Lido Active equipment. All the signals are acquired by a Personal Computer with dedicated software that control a 12 bits data acquisition board (DT2801A Data Translation, Massachusetts, USA) at a rate of 2 kHz per channel.

2.5 LE extraction - Each channel of the acquired EMG is digitally filtered to remove both motion artefacts and irrelevant high-frequency components using a band-pass filter with 3 dB cut-off frequencies from 10 Hz up to 400 Hz. The Linear Envelope (LE) is computed rectifying the signal with a digital rectifier (absolute value) and filtering by a low-pass filter with 10 Hz cut-off frequency (Butterworth 4 poles) [9].

2.6 Trial segmentation - The isokinetic test consists of repetitive flexo-extension of the leg. The quadriceps muscles are active only in the extension phase when the leg rises up. This is true for healthy subjects and non-neurological patients as well [10][11]. Since the analysis is concentrated only in the extensions, each extension phase of the entire exercise was segmented applying a classical cross-correlation technique.

2.7 Normalisation - The selected segments are interpolated using a linear interpolator to get records of the same length (2650 samples) and decimated just to obtain records of 265 points. Then the amplitude of the linear envelope is normalised. The normalisation is necessary to reduce the amplitude variability of the signal due to uncontrollable factors such as skin resistance, electrode placements and the like. Pattern average normalisation has been adopted in this study.

2.8 EMG LE grand ensemble average - To retrieve global information about muscle control strategies in the groups of normal subjects and of AKP patients the grand ensemble average of the EMG LE have been computed for all trials and all subjects within the groups. No exclusion of mis-performed trials has been made. As the isokinetic exercise is a speed-controlled movement we can suppose that, in normal subjects, exist a unique muscle control scheme. The average envelope of the EMG could represent the so-called normal profile of the movement. Such information could help the comprehension of the controlling mechanisms of the knee joint movement and the pathological conditions. The grand ensemble average was obtained performing the average on EMG LE after duration and amplitude normalisation. The grand ensemble average of the torque and the position signals were computed too.

2.9 EMG LE decomposition - To represent phase activity, the EMG LE is modelled as a summation of un-normalized gaussian pulses of various lengths, as proposed by Shavi (1992) [8]. The aim of the decomposition is to identify the various phases of the envelope. For a precise reconstruction of the EMG LE, a large number of component phases are required. The phases which have a stronger weight in the EMG LE global activity are called dominant phases. Among those, the phase having the highest amplitude is called the peak phase, while the others are called major phases [8]. To simplify EMG LE representation, only the dominant phases have been used. A threshold, defined as
the summation of the EMG global activity (area under the envelope) divided by the number of the components minus one, has been considered to discriminate such dominant phases. A limited number, ranging from 2 to 5, of dominant phases is obtained.

It is possible to give a physical significance (meaning) to these phases, in relation to the muscle effort along the exercise. The peak phase activity represents the maximum muscle effort in the extension of the leg and, in healthy subjects, it is located in the first part of the extension; major phases (the other dominant phases) represent the muscle activities to stand the strain during the extension; the other (non dominant) phases correspond only to little adjustments. The temporal position of the peak phase has been considered as a temporal identifier of the muscle activation.

3. RESULTS

3.1 Grand ensemble average. - The grand ensemble average of the signals relative to the healthy subjects group (Fig. 1 left) and the AKP patients group (Fig. 1 right) are shown in Fig1. The signals EMG LE VL, RF, VM are reported versus the percentage of the extension. The thick line represents the grand ensemble average while the thin lines represent the grand ensemble average ±1 standard deviation to show the inter-subject variability. Being the isokinetic a controlled exercise the inter-subject variability is considerably lower than in gait analysis [12].

Figure 1: Grand ensemble average of the EMG LE
The envelopes show a different activation of the muscles during the extension. For healthy subjects the EMG LE profile increases with a steep slope until the 20% of the extension (its peak), after decreases slightly until 50% of the extension and after more steeply until the end. The profile of EMG LE well correlate with the joint torque.

The profiles of the EMG LE of AKP patients relative to Vastus Lateralis and of Rectus Femoris are similar in shape respect to the healthy subjects, even if the starting slope is lower and the peak value is little delayed (about the 30% of the extension). The profile of the EMG LE of the Vastus Medialis of AKP patients is quite different from that of the healthy: the upper part of the envelope is rounded and the peak is reached at about 45% of the extension.

3.2 EMG LE decomposition - The decomposition allows the study of the modification of the EMG LE in term of the modification of its phases. As the peak phase could represents the maximum muscle effort is reasonable to study its position for each muscle and their temporal relationship. In Fig. 2 the histograms of the time occurrences of the peak phases against the angle of flexion are reported.

In healthy subjects (Fig. 2 left) the peak phases lay on the first part of the extension where the maximum muscle effort is required to accelerate the leg. It holds for all the muscles. In AKP patients (Fig. 2 right) all
the muscle peak activities are little delayed, but is particularly evident a different timing of the Vastus Medialis.

4. DISCUSSION
Probably the knee extension is one of the most practised and studied of all the isokinetic exercises, however the forces magnitude arising in the knee during the extension are not completely known. Recently Nisell and Ericson [13] proposed an analysis of the forces in the sagittal plane using anatomical and biomechanical data. They found that during an isokinetic exercise [13], the torque, shows a maximum in the range 70°-75° of flexion, depending on the movement velocity and that the patello-femoral compressive force reaches its maximum at the same range of angles. Our results for the healthy subjects are aligned with the above mentioned findings. In fact, the EMG LE peak phases are located in the same range of flexion angles (70°-75°). As the patello-femoral compressive force does not exclusively lie in the sagittal plane but it has a little component in the coronal plane, it tends to push the patella laterally. A decrease in the strength of the Vastus Medialis or an increase in that of the Vastus Lateralis results in an increase of the lateral subluxation the patella [14]. In a subluxate patella the compressive force is transmitted to the femur by a reduced weight-bearing surface. Such increased local stress generates condensation of the bone, injuries to the articular cartilage and the like.

Respect to healthy subjects, the examined AKP patients show a reduction in the torque magnitude; besides, the torque peak appears later. However, there is no significant modification in shape of the torque profile. The results agree with Werner's [15]. It is interesting to note that both a lower maximum torque and a delayed peak position contribute to reduce the compressive force [13]. These phenomena could be interpreted as an attempt to reduce pain. The pain inhibition response influences not only the global muscle strength but also the muscle activity control system. The neural muscle control tries to reduce the patello-femoral compressive force moving the maximum of activation to a higher flexion angle. This is particularly evident considering the grand ensemble average of the EMG LE of the Vastus Medialis (see Fig. 1 right). Such results suggest that the pain inhibition response is not the same for all three superficial muscles of the quadriceps. On this subject, a different effect of pain in monosynaptic and polysynaptic reflex inhibition was reported by Leroux [16]. After nociceptive stimulation, uni-articular extensors, in particular the distal fibres of the Vastus Medialis, show a longer and stronger inhibition than the bi-articular Rectus Femoris.

The comparison of the grand ensemble average of EMG LE, between healthy subjects and AKP patients provides a rapid and objective technique to assess their differences. But this method is not effective for diagnosis purpose because of the high inter-subjects variability of the EMG LE due to measurement uncertainness and biological differences [17]. The results obtained from the phase decomposition method seem interesting. The sequences of the peak activity (the maximum effort during the extension of the leg) are significantly different between the two groups, as specified in the results. The lack of the mechanical balance between the two Vastus is probably the cause of the difference. The impossibility of co-activating the two muscles for the different inhibition reflex, leads to the use of the Rectus Femoris, as the lateral component in the coronal plane of the force produced by this muscle is low and the consequential lateral subluxation of the patella is negligible. The mean position of the peak phase in AKP subjects is later than that of the healthy ones. Hence the AKP subjects effect the maximum effort at lower flexion angle to reduce the patellar compressive force and they select the Rectus Femoris to reduce the subluxation of the patella.

5. CONCLUSION
A clear difference appears in force generation (dosage, amount, and activation level) during muscle contraction between Healthy subjects and AKP patients, particularly in the Vastus Medialis activation. These differences (modification) are not only due to the weakness of the Vastus Medialis, as reported in previous works, but also to a modification of the neural control strategy of the quadriceps muscles. AKP patients delay the activation of the Vastus Lateralis and Vastus Medialis respect to the Rectus Femoris in order to minimise the painful effect of the mechanical unbalance on the patella.

To describe correctly these abnormalities simple global parameters extracted by the LE-EMG have been not effective. The use of the LE-decomposition methods has been found appropriate.
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