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Using the discrete wavelet transform in assessing the effectiveness of rehabilitation in patients after ACL reconstruction

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Purpose: The purpose of the current study was to assess the effectiveness of rehabilitation in patients after anterior cruciate ligament reconstruction (ACLR) using a wavelet analysis of the torque-time curve patterns of the extensors of the affected knee. The analysis aimed at the quantitative evaluation of irregularities in these torque-time patterns. *Methods*: The study involved a group of 22 men who had had ACL reconstruction. The torque-time characteristics were recorded 3, 6 and 12 months after the surgery by an isokinetic dynamometer. They were then examined using the orthogonal Daubechies 4 (Db 4) and biorthogonal Bior 3.1 wavelets. *Results*: A statistical analysis of the results revealed significant differences in values of the high-frequency energy stored in the details of the signal from the dynamometer between the first and last measurements, both for the Db 4 ($p \le 0.023$) and Bior 3.1 ($p \le 0.01$) wavelets. These differences were found in 73% of patients whose curve patterns were analysed using the Db 4 wavelet and in 82% of patients in the case of the Bior 3.1 wavelet. *Conclusions*: The wavelet transform proved to be an effective research tool in the qualitative evaluation of irregularities occurring in the curve patterns of the torque generated by the extensors of the ACL reconstructed knee. The findings of the study suggest that time-frequency analyses of these characteristics can be of practical importance, as they help assess the state of the patient's knee joint and his progress in rehabilitation after ACLR.

Key words: *wavelet, ACL, rehabilitation*

1. Introduction

Rehabilitation after anterior cruciate ligament reconstruction (ACLR) is a long process which needs to be constantly monitored. Although implementing accelerated rehabilitation protocols [20] has helped reduce the duration of intensive therapy to approximately 6 months, most patients are still unable to regain normal knee function a year from the surgery [1], [7]. Traditional methods of monitoring the effectiveness of rehabilitation include using the Lysholm/Tegner scales as well as arthrometers. However, the two grading scales are subjective in nature, and the results of the measurement of laxity in the knee joint do not always correspond with the level of knee function [24].

Biomechanical tests are thus commonly used in order to monitor the patient's progress during rehabilitation. These tests most frequently involve having the patient perform jumps and measuring the strength

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of the muscles using isokinetic dynamometers. This is described in the literature review by Kvist [15], who listed the methods of evaluating the function of the knee joint after ACL injury used by 30 different authors. Twenty-six of them used jumping tests and sixteen measured the torque of the knee flexors and extensors in isokinetic conditions in order to assess the effects of rehabilitation.

When conventional methods of evaluating the knee joint after ACLR using an isokinetic dynamometer are applied, the value which is analysed most often is the peak torque of the knee flexors and extensors or other discrete variables included in the measurement protocol [11]. Yet, knowing the maximum value of these variables is insufficient for assessing the way the torque is generated in the entire range of motion.

An additional approach that can be used to confirm the effectiveness of rehabilitation after ACL surgery is a quantitative assessment of irregularities in the torque-time curve pattern. A smooth curve is likely to indicate good control of force by the neuromuscular system [25], while an irregular curve indicates abnormalities and its shape can be affected by the presence of high-frequency components in a signal. An irregular shape of the curve in persons with ACL injuries has been reported by several researchers [2], [10], [21], [23]. One of the quantitative approaches to evaluating irregularities in these patterns, described by Tsepis et al. [26], is based on the fast Fourier transform. The authors found significant differences in the high-frequency content of ACL-deficient knees compared to healthy ones.

However, it needs to be emphasised that this popular method of analysing signals in the frequency domain assumes that the signal is stationary, whereas the isokinetic torque-time characteristics are non-stationary. That is why such signals need to be decomposed using functions selective both in time and frequency. This can be done through the wavelet transform which has already been successfully applied in analysing postural sway [4], [13], EMG signals [12], [14], speech signals [5], and in classifying gait patterns [18].

To the best of our knowledge, wavelet analyses of the irregularities in the torque-time curve of the knee extensors during post-ACLR rehabilitation have not been performed so far, despite the fact that the frailty of this muscle group is one of the main symptoms of abnormal knee function [3], [17], [19].

Both the knee joint and the cruciate ligament contain numerous mechanoreceptors such as Ruffini endings, Pacini corpuscles, and Golgi tendon organs [8], [22]. Removing the anterior cruciate ligament, replacing it with a graft, and altering the structures of the knee joint during surgery exert an impact on the function of the lower limb. Abnormalities occurring in the form of post-surgical disturbances in the way information is delivered to the central nervous system by the mechanoreceptors in the knee joint or a complete lack of such information are subtle in nature, and it can be hypothesised that the wavelet transform can indirectly confirm the presence of such abnormalities.

The aim of this paper is to assess the effectiveness of rehabilitation after ACLR using a wavelet analysis of the torque-time curve of the knee extensors. We hypothesised that the high-frequency component of the energy stored in the details of the decomposed signal would decrease over the course of rehabilitation.

2. Methods

2.1. Subjects

The study involved a group of 22 men (age: 26.5 ± 3.2 years; height: 178.6 ± 5.2 cm; mean body mass in the three measurements performed in the study: 79.1 ± 8.9 kg) who had had ACL reconstruction. The men suffered an ACL injury during recreational activity. All of them underwent pre-operative rehabilitation which was to help them regain full extension of the knee joint. After the pain and inflammation subsided, they were operated on by the orthopaedist who had been treating them. The surgeries were performed about 6 weeks after the injury. The arthroscopic anterior cruciate ligament reconstructions were completed using an anatomic single-bundle technique. The replacement material was four-strand semitendinosus and gracilis tendon grafts. After the surgery, the subjects completed an accelerated rehabilitation programme. The six-month intensive programme was based on the subjects exercising individually at home [7]. After completing the programme, the subjects were still monitored once a month for half a year by a physical therapist.

In order to obtain referential curves, we tested a group of 20 students enrolled in the Physical Education programme at the Józef Piłsudski University of Physical Education (age: 22.3 ± 0.9 years; height: 179.3 ± 5.2 cm; body mass 74.7 ± 7.1 kg) who declared they had never sustained injuries to the knee joint and were not experiencing any pain in the joint.

Before the measurements were performed, the subjects were informed about the aim of the study and consented to participating in it. The study was approved by the Senate Research Ethics Committee of the University of Physical Education in Warsaw.

2.2. Signal acquisition

Isokinetic measurements were performed 3, 6, and 12 months after the surgery, using the Biodex System 3-PRO dynamometer (Biodex Medical Systems, Inc., Shirley, NY). Each measurement was preceded with a 5-minute warm-up on a bicycle ergometer. The subjects adopted the standard sitting position and were stabilised using straps, as recommended by the manufacturer of the dynamometer. The range of motion was restricted to 90 degrees. Knee flexion and extension torque was evaluated in isokinetic conditions, at the commonly used constant angular velocity of 60 deg/s [6], [7], [11]. The test included a series of 5 extending and flexing movements. Bearing in mind the aims of the current study, only the torque-time curves of the extensors in which the subjects achieved maximum values of muscle torque were included in the analysis.

The raw data from the dynamometer were digitized at a sampling frequency of 100 Hz. They were then filtered using a low-pass Butterworth filter with a cut-off frequency of 25 Hz. The high cut-off frequency was selected in order to preserve any short-term irregularities in the torque-time curves caused by the ACL rupture and changes in the structures of the knee after surgery.

2.3. Wavelet transform

The wavelet transform consists in representing a signal in the form of short waveforms called wavelets. It is being used more and more frequently to analyse aperiodic and discrete noise signals. An analysing wavelet is a scaled version of the mother wavelet and can generally be represented as

$$g_{a,b}(t) = \frac{1}{\sqrt{a}} g\left(\frac{t-b}{a}\right), \qquad (1)$$

where $g_{a.b}(t)$ is the analysing wavelet, $g(t)$ is the mother wavelet, while a refers to the scale and b to the translation.

A continuous wavelet transform (CWT) is defined as

$$CWT\ (a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t) \cdot g\left(\frac{t-b}{a}\right) dt, \qquad (2)$$

where $x(t)$ represents the signal, $a \in \boldsymbol{R}^+$ and $b \in \boldsymbol{R}$.

Parameter a makes it possible to define the frequency range, while b controls the translation of the wavelet function. The transformation image obtained in this way resembles a Fourier spectrogram. It is, however, characterised by variable resolution both in frequency and time domains. For low frequencies, the time window is wide and the frequency window is narrow, whereas the opposite applies to high frequencies.

Although continuous values for the scale parameter a and translation b make it possible to adapt these parameters to the analysis of particular signals, in many cases applying this procedure is time-consuming and redundant. That is why the discrete wavelet transform (DWT), where parameters a and b are discretised, has been introduced. The following discretisation is commonly used

$$a = 2^m, \quad b = k \cdot 2^m. \qquad (3)$$

Substituting (3) into (1), the discrete wavelet function can be expressed as

$$g_{m,k}(t) = \frac{1}{\sqrt{2^m}} g\left(\frac{t - k \cdot 2^m}{2^m}\right) \qquad (4)$$

or more compactly,

$$g_{m,k}(t) = 2^{-m/2} g(2^{-m} t - k), \qquad (5)$$

where the integers m and k are responsible for the wavelet dilatation and translation. The power-of-two logarithmic scaling (equation (3)) forms the dyadic grid, which provides the construction of an orthogonal wavelet basis.

There is a close link between DWT and the theory of multi-resolution analysis, according to which signals can be approximated with varying degrees of accuracy using scaling functions and expressed by means of orthogonal wavelets. At the M level of approximation, a finite length discrete signal $x_d(t)$ can thus be represented as a sum of shifted scaling functions $\varphi(t)$ multiplied by appropriate approximation coefficients and so-called details associated with the wavelets

$$x_d(t) = \sum_k A_{M,k} \varphi_{m,k} + \sum_{m=1}^{M} \sum_k D_{m,k} g_{m,k}(t) = x_M(t) + \sum_{m=1}^{M} d_m(t), \qquad (6)$$

where coefficients $A_{M,k}$ represent the approximation of the signal for the M scale, and $D_{m.k}$ are the detail coefficients. Higher-level approximation and detail coefficients are obtained by filtering the approximation coefficients from the lower level. At $m = 0$ the approximation coefficients are equal to the signal. At $m = 1$ the signal is decomposed into approximation and detail coefficients. The approximation coefficients are then filtered at $m = 2$ and are again decomposed into approximation and detail coefficients (Fig. 1).

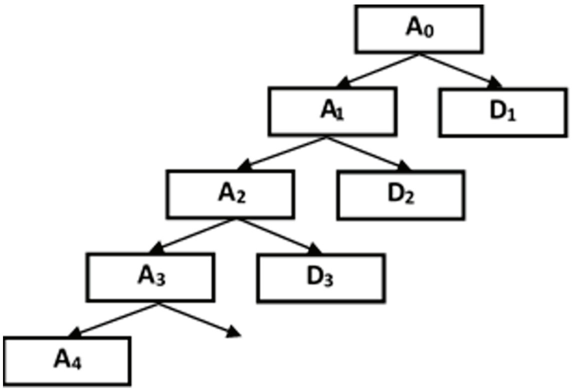

Fig. 1. Multi-level signal decomposition

The total energy of the signal E is calculated as the sum of the squares of the approximation coefficients for the M scale plus the sum of squared detail coefficients over all scales,

$$E = (A_M)^2 + \sum_{m=1}^{M} (D_m)^2 . \quad (7)$$

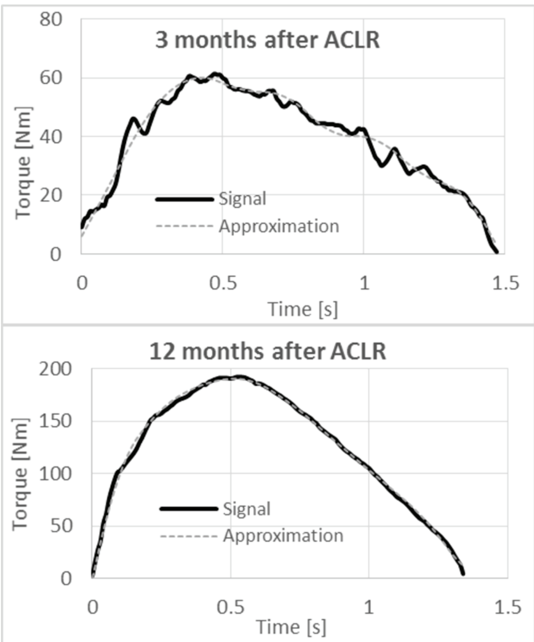

Fig. 2. Original torque-time curve (in black) and approximation curve (grey dashed line) obtained for scale 4 using the Bior 3.1 wavelet after 3 months of rehabilitation (top) and after 12 months of rehabilitation (bottom)

The choice of the type of wavelet and the number of decomposition scales is determined by the type and duration of the signal [13].

In this study, the biorthogonal Bior 3.1 and orthogonal Daubechies Db 4 wavelets were used. We selected the type of wavelet and number of scales which made it possible to obtain a smooth approximation torque-time curve. Figure 2 shows a sample original curve (in black) and its approximation (grey dashed line), obtained using a Bior 3.1 wavelet for a scale of 4. Increasing the number of scales further caused the approximation curve to deviate significantly from the original one. The curves in Fig. 2 (top) were recorded for one of the patients after he underwent 3 months of rehabilitation. Figure 2 (bottom) shows the curves that were obtained 12 months after ACLR. There are hardly any fluctuations in Fig. 2 (bottom), and the approximation curve almost entirely corresponds with the original curve.

The irregularity of the torque-time curve of the knee extensors was specified as the percentage of the energy of the details in total energy

$$\delta = \frac{\sum_{m=1}^{M} (D_m)^2}{E} * 100\% . \quad (8)$$

3. Results

Figure 3 shows slightly smoothed torque-time curves of the knee extensors, which were later processed using the discrete wavelet transform. There are evident differences between peak torque values recorded after 3 and 6 months of rehabilitation (Fig. 3, top), but the shapes of the curves remain similar. When one compares these curves with those obtained a year after surgery (Fig. 3, bottom left), a further increase in the peak torque of the knee extensors is noted; moreover, most characteristics are less undulated.

When the characteristics measured in the patients after 12 months of rehabilitation (Fig. 3, bottom left) are compared with those recorded for the group of students (Fig. 3, bottom right), it is apparent that the oscillations in the curves of the patients are mostly due to the ACL rupture. The smooth curves obtained for the students indicate that vibrations originating from the dynamometer had a limited impact on the results of the measurement.

Figure 4 shows the results of the discrete wavelet analysis of the curves recorded for the patients after 3

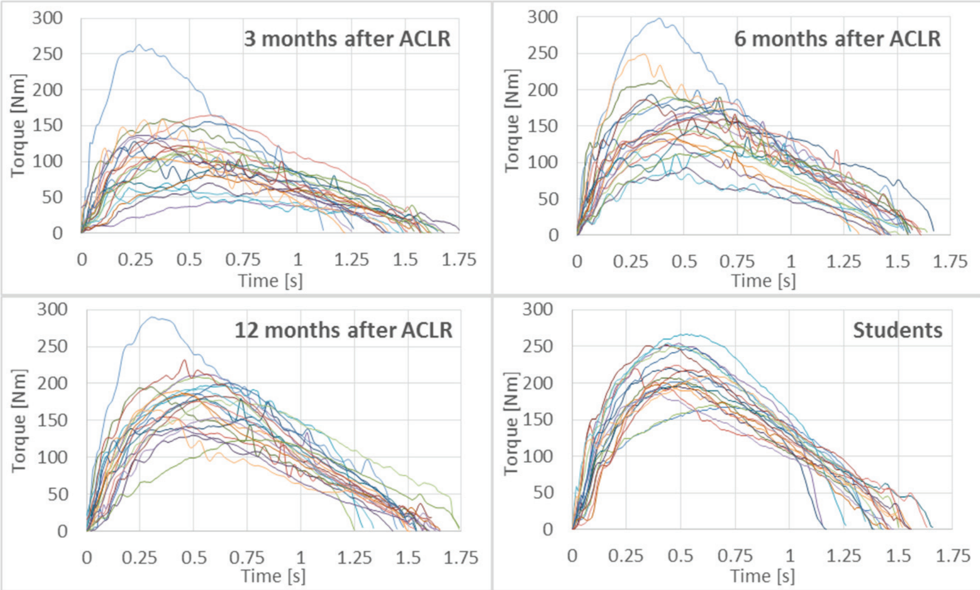

Fig. 3. Torque-time characteristics recorded 3 months (top left), 6 months (top right), 12 months (bottom left) after ACLR and torque-time curves of the students (bottom right)

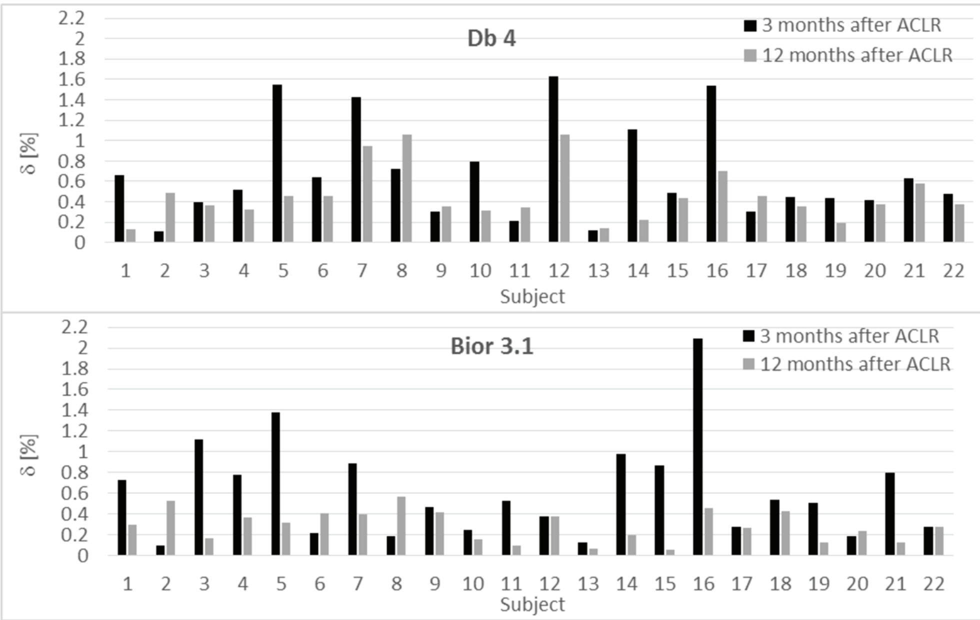

Fig. 4. The parameter δ calculated for each patient 3 and 12 months after ACLR using the Db 4 wavelet (top) and the Bior 3.1 wavelet (bottom)

and 12 months of rehabilitation. Large differences in the values of the parameter δ can be observed, ranging from 0.05% (patient 15, Bior 3.1 wavelet) to 2.09% (patient 16, Bior 3.1 wavelet). Lower values of the parameter δ after 12 months of rehabilitation were found in 16 out of 22 patients (73%) for the Db 4 wavelet and in 18 patients (82%) for the Bior 3.1 wavelet.

The Shapiro–Wilk test showed that in 8 sets of δ values, the data were normally distributed only for the Db 4 wavelet 6 months after surgery, the Bior 3.1 wavelet 12 months after surgery and in the group of students. The Friedmann test comparing the mean value of the parameter δ 3, 6 and 12 months after the surgery showed significant differences among the means analysed. Post hoc testing revealed that the mean δ values were significantly lower between the first and the third measurement both for the Db 4 ($p \leq 0.018$) and Bior 3.1 ($p \leq 0.042$) wavelets (Table 1). Student's t test also revealed statistically significant differences ($p \leq 0.003$) between the mean values of the parameter δ for the patients 6 months after ACLR and the students for the Db 4 wavelet, whereas the Mann–Whitney U test

Table 1. Mean percentage values of the parameter δ obtained for the patients in three stages of rehabilitation and for the students

Wavelet	3 months after ACLR	6 months after ACLR	12 months after ACLR	Students
Db 4	$0.67 \pm 0.41^*$	$0.55 \pm 0.24^\#$	$0.45 \pm 0.26^*$	$0.39 \pm 0.11^\#$
Bior 3.1	$0.61 \pm 0.48^*$	$0.41 \pm 0.24^\#$	$0.28 \pm 0.15^*$	$0.24 \pm 0.12^\#$

Pairs of identical symbols in the superscript in the rows of the table indicate statistically significant differences between the values of the parameter δ ($p \leq 0.05$).

showed significant differences for the same pair of variables for the Bior 3.1 wavelet ($p \leq 0.014$) (Table 1).

Figure 5 presents the distribution of the high-frequency energy stored in the details of the signal during the knee extension cycle. The cycle has been divided into 10 right-closed intervals $P_i \in (0.1*(i-1), 0.1*i>$, $i = 1 \div 10$. It is visible that regardless of the phase of rehabilitation and the wavelet, most of this energy (from 60.3% for Bior 3.1 three months after ACLR to 77.8% for Db 4 one year after ACLR) is stored in the first three intervals of the cycle. It is also worth noting the low level of the high-frequency energy during the steady movement of the lever arm of the dynamometer (the smallest value being 0.9% at P_7 for Db 4 twelve months after ACLR) and the increase in the value of this energy at the end of the cycle (with the greatest value at P_{10} for Bior 3.1 twelve months after ACLR).

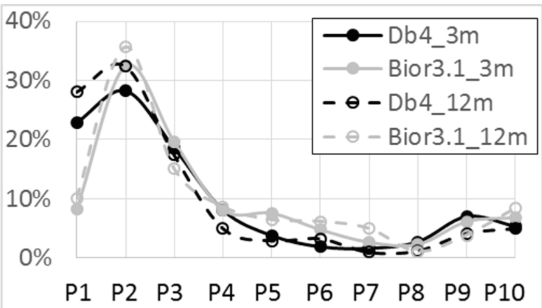

Fig. 5. High-frequency energy distribution during the knee joint extension cycle

4. Discussion

The results of the study indicate that during rehabilitation after ACLR, there was a decrease in the high-frequency energy stored in the details of the signal representing extension torque-time curves of the knee joint that had undergone surgery. A lower level of the energy in the second stage of rehabilitation was found in 73% of patients in the case of the Db 4 wavelet and in 82% of patients when the Bior 3.1 wavelet was used. Identifying such decreases can be of practical importance in clinical evaluation of the function of the knee joint. Decreases in the high-frequency energy during rehabilitation were found regardless of the wavelet that was used, although when the Bior 3.1 wavelet was applied, differences were found for more patients.

The findings of the current study thus correspond qualitatively with those presented by Tsepis et al. [26], who used the traditional Fourier analysis to compare the power spectra of the extensors and flexors of ACL-deficient and healthy knees. The authors found out that the frequency content in the power spectrum of the knee extensors of the injured leg was higher by 10.6% in 73% of the subjects at the 95% level of signal power.

However, applying the Fourier transform in analysing such signals raises certain issues. According to Fourier's theory, a signal can be decomposed into a series of infinite sine and cosine signals. When the Fourier analysis is applied in practice, it is impossible to use infinite limits of summation, as signals like isokinetic time-torque curves are of a finite length in the time domain. This means that the signal is multiplied by a rectangular window. Based on the properties of the Fourier transform, the obtained spectrum is a convolution of the spectra of the signal and window function rather than the spectrum of the signal. The rectangular window is characterised by a wideband spectrum, and this has a considerable impact on the results of the analysis. Moreover, the analysed signals have different duration times, which means that the width of the windows varies. This leads to differences occurring in the proportions between particular frequency components in the resultant spectrum. Another drawback is that some parts of the spectrum associated with irregularities in the torque-time curve pattern cannot be extracted from the spectrum of the original curve. The discrete wavelet transform poses no such problems. The signal is decomposed into a series of short-duration waves called wavelets, which eliminates problems having to do with windowing and makes it possible to analyse any selected part of the signal. A crucial advantage of this approach, however, is the possibility of identifying the component energies of the main signal, that is, separating the approximation from the details.

The analysis of selected components of the signal showed that more than 60% of the high-frequency energy was stored in the first part of the extension cycle. This is due to the strong contraction of the quadriceps in this phase of the cycle, as it is the torque generated by this muscle that causes the lever arm of the dynamometer to rotate. This finding of the study can be of practical importance, because it suggests that exercise aimed at improving the contraction of the quadriceps should be introduced early in the process of rehabilitation after ACL rupture [9].

The lack of significant differences in the high-frequency energy stored in the details of the signal between the first and the second measurements and the presence of such differences between the patients after 6 months after ACLR and students proved that the knee joint did not function properly despite the fact that the patients had completed the rehabilitation programme. Therefore, six months seem to be not enough for the reconstructed knee joint to return to its preinjury physical level. This observation is in line with those reported in [1], [7], [16].

The fact that statistically significant differences were found in the distribution of the energy of the signal between the phases of rehabilitation examined in this study can be interpreted as evidence of damage to the mechanoreceptors in the ligament or an altered pattern of the activation of the knee extensors [8], [22]. As the patient recovers, the tissue in the ligament regenerates, and the alterations in the knee joint caused by the surgery disappear. The speed at which these slow and subtle changes take place can be recorded in a precise time-frequency analysis.

In our discussion of the wavelet analysis of the signal from the isokinetic dynamometer, we should also mention the potential impact of two factors which may limit the conclusions drawn from this study. The first factor is the inaccuracy of the measurement of the torque of the knee extensors and flexors caused by a lack of alignment between the axis of rotation of the knee joint and the axis of the dynamometer. This problem is discussed in detail in [7].

The other factor has to do with the way the time-frequency analysis was conducted. The final result was affected by a range of parameters, such as the type of analysis (continuous or discrete), type of wavelet (we used, for example, 4-point and 8-point digital filters for the Bior 3.1 and Db 4 wavelets, respectively), and number of scales, all of which were selected subjectively. Although these issues have been well explored in the classical analysis of signals, the signals from instruments used in biomechanics require further investigation.

Finally, we would like to emphasize that in our analysis we deliberately concentrated on males only, as such a homogenous group lets us focus on our methodology.

To conclude, the wavelet transform proved to be an effective research tool in the analysis of the isokinetic time-torque curve patterns generated by the extensors of an ACL reconstructed knee. Quantitative analyses of the irregularities occurring in these characteristics can also be of clinical importance, as they can help to evaluate the state of the patient's knee joint as well as his/her progress in rehabilitation after ACLR.

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