

Original research papers

WAVELET ANALYSIS OF REARFOOT LOADING OF PATIENTS AFTER MEDIAL PATELLOFEMORAL LIGAMENT (MPFL) RECONSTRUCTION

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Abstract

Introduction. Patellar instability in younger patients is a common injury (3.3% of all knee injury episodes) and the most frequent dislocation of the knee observed. The sensitivity and reliability of clinical diagnostic tests after medial patellofemoral ligament (MPFL) reconstruction remain unclear and biased. The primary aim of the present study was thus to detect, using wavelet analysis, differences in the rearfoot loading of the operated limb of patients after MPFL reconstruction. The authors hypothesised that applying this specific examination technique would allow for more accurate and less biased clinical results evaluation. **Material and Methods.** The study involved a group of 15 female subjects (age: 22.8 ± 6.3 years; weight: 58.5 ± 5.1 kg) after MPFL reconstruction and a control group of 29 healthy females (23.2 ± 2.8 years; 61.1 ± 7.7 kg). The subjects performed a 30-second classic Romberg test on a treadmill (Noraxon FDN-T) equipped with a matrix of baroresistive sensors to measure ground reaction forces. Time-frequency analysis of the signal originating from the treadmill was done using an analytic Morse wavelet. **Results.** The results indicate differences in visual control and vestibular stability in patients before and 3 months after a surgery. They are characterised by a deficit of energy attributed to visual control in favour of an excess of energy associated with vestibular control. Patellar instability patients show greater energy expenditure to maintain body balance for at least 6 months after MPFL reconstruction. **Conclusions.** Patellar instability patients have increased vestibular control while maintaining balance. Our results suggest an extended rehabilitation period for patients after MPFL reconstruction beyond 6 months.

Key words: MPFL, reconstruction, wavelet analysis

Introduction

Patellar instability in younger patients is a common injury (3.3% of all knee injury episodes) and the most frequent dislocation of the knee observed [1, 2, 3]. The medial patella femoral ligament (MPFL) serves as the primary stabilizer of the patellae responsible for 70% of lateral displacement prevention forces. The patellar dislocation episodes correlate with the MPFL rupture in 90-100%. MPFL limited healing potential advocates the primary surgical reconstruction with the use of variety of techniques, followed by a demanding rehabilitation protocol [4, 6]. In the literature, over 90% of good to excellent clinical results are reported based on clinical and radiological assessment [7, 8]. Clinical assessment is crucial in all stages of diagnosis and treatment. It is essential to reveal patients' satisfaction and clinical outcome [9, 10]. However, the sensitivity/specificity and reliability/validity of clinical diagnostic tests based on an individual, subjective examination remains unclear and biased [11, 12]. This fact advocates more objective, observer independent and reproducible techniques of clinical assessment. Gait and posture control evaluation was successfully described as supportive in this field [13].

Clinical assessment can be complemented by the use of various biomechanical methods. One such method is wavelet analysis of signals generated by the human body. Chapter six of Addison's book published more than two decades ago discusses and provides references to dozens of articles in this field [14].

Wavelet analysis has also been used to assess the knee condition of patients after arthroscopic anterior cruciate ligament reconstruction (ACLR). For example, the EMG signal from seven muscles of the lower limb during a single leg hop of such patients [15], the time courses of the moments of the flexors and extensors of the knee joint obtained with an isokinetic dynamometer [16] as well as postural sway on a force platform [17] were investigated.

The time courses of the centre of pressure (COP) of the feet form the basis of body sway studies. Wavelet analysis makes it possible to determine the time-frequency characteristics of these courses, which is of significant cognitive and practical importance due to their non-stationary nature [18, 19]. It is believed that body sway frequencies below 0.1 Hz can be attributed to visual control, higher frequencies up to about 0.5 Hz to vestibular control, while frequencies above 1 Hz are associated with somatosensory activity [20, 21, 22].

COP time trajectories are generally determined using traditional force platforms that process the signal from several strain gauge or piezoelectric sensors (e.g. Kistler, Kistler Instrumente AG, Switzerland; AMTI, AMTI Force & Motion, USA). Platforms with integrated arrays of baroresistive sensors (e.g. Zebris FDM-S, Zebris Medical GmbH, Germany; Noraxon FDN-T, Noraxon USA Inc.) are also used in biomechanics laboratories or physiotherapy offices. These devices make it possible to record and determine the resultant ground reaction forces acting on different parts of the feet during standing, gait or running. Given the

increasing popularity of platforms with baroresistive [23, 24, 25] arrays, it seems reasonable to carry out a time-frequency analysis of such output signals generated by such devices. To the authors' knowledge, such an analysis has not been sufficiently described in the literature.

With this in mind, the primary aim of the present study was to detect, using wavelet analysis, differences in the rearfoot loading of the operated limb of patients after MPFL reconstruction. The authors hypothesised that applying this specific examination technique would allow for more accurate and less biased clinical results evaluation. An additional aim was to test the discriminative capabilities of the signal derived from a baroresistive platform.

Material and Methods

Subjects

The study involved a group of 15 female subjects (age: 22.8 ± 6.3 years; weight: 58.5 ± 5.1 kg) after MPFL reconstruction and a control group of 29 healthy females (23.2 ± 2.8 years; 61.1 ± 7.7 kg). The subjects were provided with information on the research process and profits related to participating in the study. The research was initiated in 2021 and was conducted in accordance with the ethical standards of the Helsinki Declaration and was approved by the University Research Ethics Committee.

Surgical procedure and rehabilitation protocol

Patients with patellar instability with at least two patellar dislocation episodes were scheduled for an arthroscopic evaluation performed in each case to exclude the other joint pathologies (ACL lesion, meniscal status). During the same procedure the MPFL was reconstructed from autologous gracilis tendon and placed in the „V” shape technique. Trochlear dysplasia was not addressed surgically. Rehabilitation protocol included the postoperative PRICE technique, brace immobilisation (0-30 deg initially for 7-14 days) and walking with crutches. Full weight bearing was allowed after 2-3 weeks as tolerated. Rehabilitation visits included manual therapy and exercise adjustment of the next steps based on “home exercise program” (HEP). Patients were instructed to follow the schedule twice a day (self-controlled). Finally, 6-8 weeks after the surgery, patients were encouraged to use the gym exercise set. That part included bicycling, open and closed kinematic exercises and swimming. Work/school return was advised 6-8 weeks postoperatively.

Measurements

The subjects performed a 30-second classic Romberg test on a treadmill (Noraxon FDN-T) equipped with a matrix of baroresistive sensors to measure ground reaction forces. The sampling frequency of the matrix was 100 Hz. Prior to the Romberg test, the subjects completed a 20-second free standing test on the platform to adapt to the new surface and body configuration required for this trial.

Static treadmill tests were also carried out at the start of the measurements. These consisted of 30-second test-retests for 20, 50 and 80 kg weights placed on sports shoes at the point of contact between the subjects' feet and the treadmill.

Data processing

The time courses of the ground reactions for the front and back of the foot of the subjects were de-averaged and pre-processed by smoothing with a low-pass filter with a cut-off frequency of 5 Hz. The two waveforms were found to be approximately symmetrical with respect to the time axis (Fig. 1). This means

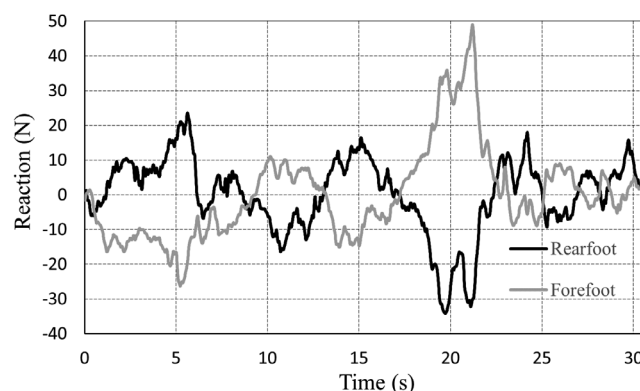


Figure 1. Pre-processed time courses of vertical ground reactions acting on the foot of the operated limb in one of the subjects

that the loading of the rearfoot corresponds to the unloading of the forefoot and vice versa.

The time courses of the rearfoot loading were therefore selected for further analysis. Once the 30-second signal segments had been selected, they were zero-padded bilaterally to a length of 9000 points, which guaranteed a minimum frequency value of $f = 0.0391$ Hz for the highest-scale wavelet.

Time-frequency analysis was carried out using an analytic Morse wavelet available in the Wavelet Toolbox library (Matlab, MathWorks, USA). After the wavelet coefficients were determined, the total energy of the signal in the rectangular region $<30s; 60s> \cap <0.05Hz; 5Hz>$ was calculated (Fig. 2 and Fig. 3). The rectangular region was defined inside the influence cone, which reduced the contribution of edge effects in the computation of energy values. We also computed the energy contained in the three frequency bands $0.05 < f \leq 0.1$, $0.1 < f \leq 0.5$ and $0.5 < f \leq 5$ and the ratio of these energies to the total energy of the signal.

The normality of the energy distributions for the individual frequencies and the energy ratios in the three analysed bands was initially checked using the Shapiro-Wilk test. As the energy did not have normal distributions, a uniform regression approach was used for all variables under study. One version of the linear mixed model, the random intercept model, was used in the calculations. Computations were performed in the R environment (R Foundation for Statistical Computing, Austria) using the *lme* function from the *nlme* package [26]. The function was called with the *corAR(1)* argument which allowed the correlation between adjacent repeated measurements to be included in the calculations.

Statistical significance was set at $p < 0.05$.

Results

Figure 2 shows a scalogram of a subject from the control group, for whom the energy ratios (26.4%; 58.3%; 15.2%) in the three frequency bands analysed correspond approximately to the average results for this group (Tab. 1). The concentration of energy in the first frequency band is visible.

Figure 3 presents a scalogram of one patient before MPFL reconstruction, for whom the energy ratios (19.2%; 65.7%; 15.9%) in the three frequency bands analysed correspond approximately to the average results for the patient group (Tab. 1). The concentration of energy can be observed in the second frequency band.

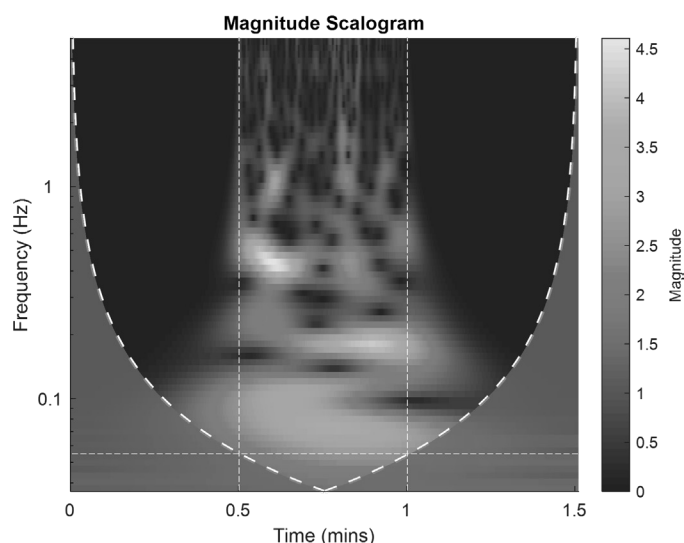


Figure 2. Scalogram of one of the healthy subjects (subject 3)

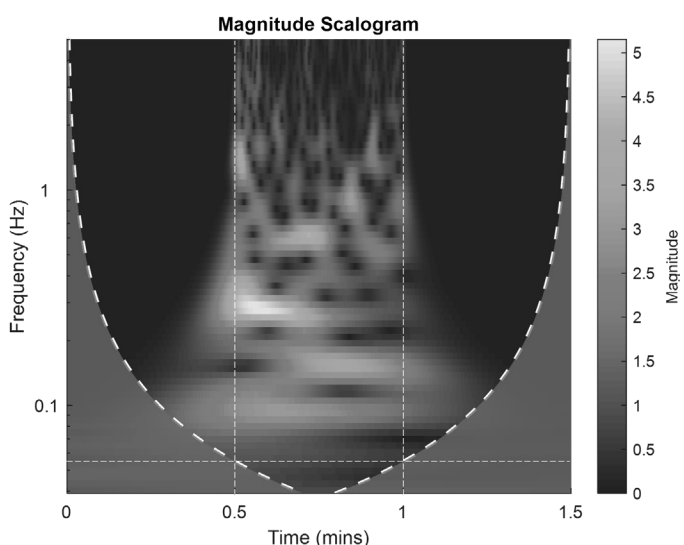


Figure 3. Scalogram of one of the patients before MPFL reconstruction (patient 15)

Figure 4 shows a quantification of the relative energy distribution for both analysed subjects. The dots correspond to the frequencies assigned to the distinct Morse wavelets.

Statistically significant differences were only found in the first and second frequency bands between the control group and the patients before and 3 months after MPFL reconstruction (Tab. 1). There were no statistically significant differences in the third frequency band, no differences between the control group and patients 6 months after MPFL reconstruction and no significant differences between measurements in the control group.

Figure 5 shows the mean waveforms of total signal energy as a function of the frequencies assigned to each Morse wavelet scale. No significant differences were found between the energy levels at individual frequencies for the three patient measurements. However, differences in energy values between the patients and the control group up to a frequency of $f = 0.88$ Hz were found to be significant. A shift in maximum energy values towards lower frequencies for patients 6 months after surgery is also evident.

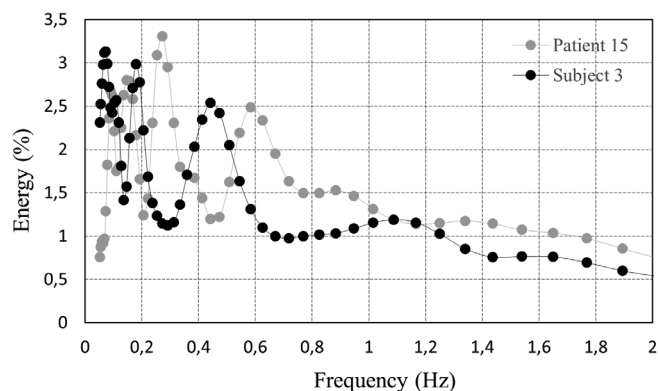


Figure 4. Percentage ratio of energy contained in three frequency bands to total energy for both subjects

Table 1. Percentage ratio of energy contained in three frequency bands to total energy

Measurement	$0.05 < f \leq 0.1$	$0.1 < f \leq 0.5$	$0.5 < f \leq 5$
Control (first measurement)	23.6 ± 7.6	61.0 ± 6.6	15.4 ± 3.9
Before reconstruction	$17.9 \pm 2.9^*$	$66.8 \pm 3.7^\#$	15.2 ± 3.7
3 months after reconstruction	$18.5 \pm 4.8^*$	$64.5 \pm 5.4^\#$	17.4 ± 5.5
6 months after reconstruction	20.3 ± 6.2	63.5 ± 6.1	16.2 ± 3.6

Note: asterisks and hashtags in the columns indicate statistically significant differences ($p < 0.05$) with respect to the control group.

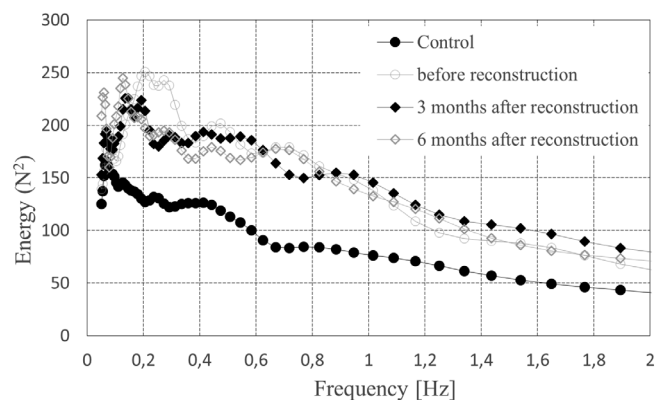


Figure 5. Mean total energy of the signal

Table 2 shows the average energy ratios from the six trials for the three frequency bands and the intraclass correlation coefficients (ICC) obtained during the static trials.

Figure 6 illustrates test-retest reliability under static conditions with a load of 50 kg. They confirm the high reliability of such a measurement.

Table 2. Average energy ratios and ICCs for static tests

Frequency band	Energy ratio (%)	Load (kg)	ICC
$0.05 < f \leq 0.1$	31.2	20	0.97
$0.1 < f \leq 0.5$	43.2	50	0.94
$0.5 < f \leq 5$	25.6	80	0.93

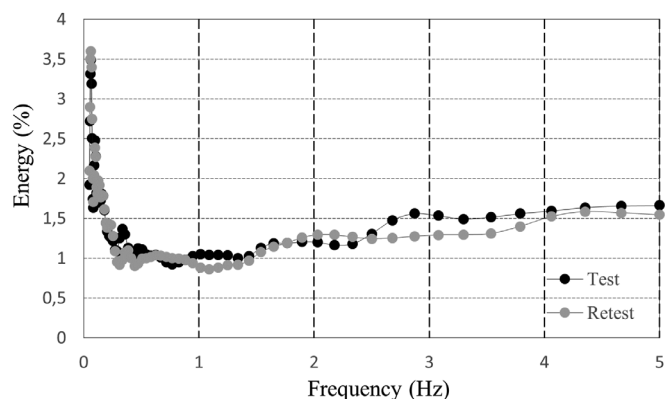


Figure 6. Test-retest reliability for percentage energy distribution when the platform is loaded with a 50 kg weight

Discussion

One of the primary aims of the study was to use time-frequency analysis to identify differences in postural stability between pre- and post-MPFL reconstruction patients and healthy subjects. The energy distribution in the three frequency bands obtained by wavelet analysis was taken as the discriminating factor between the two groups. The results showed the presence of statistically significant differences in frequency bands below 0.1 Hz and in the right-closed interval from 0.1 to 0.5 Hz. Assuming that the criteria used in the time-frequency analysis of COP trajectories [17, 20, 21, 22] can be transposed to the time series of partial ground reactions, our results indicate differences in visual control and vestibular stability in patients before MPFL reconstruction. They are characterised by a deficit of energy attributed to visual control in favour of an excess of energy associated with vestibular control. A similar energy shift effect in the two lowest frequency bands was noted when examining COP trajectories for free standing with eyes open and closed [27] and in judokas according to their level of competition [28].

A study of this phenomenon was also conducted by Lyu et al. [29] analysing the effect of muscle fatigue on changes in the centre of balance control. They noted an increase in vestibular control to a decrease in visual control as a compensatory effect in the central nervous system in response to neuromuscular deficits. The inability to fully address these results is due to the fact that he studied healthy subjects. Healthy and physically active individuals have significantly better stabilometric parameters [30]. Given that patients with patellar instability have kinesophobia [31], their level of motor activity is significantly reduced. This significantly affects the decrease in muscle strength, their faster fatigue and, analogous to the results of the mentioned authors, may contribute to a shift of the balance control centre towards vestibular control.

Figure 5 can be interpreted in a similar way, showing a significantly higher expenditure of total energy to maintain standing throughout the study period of patients with patellar instability. Indeed, the weakening of lower limb muscle strength impairs the ability to maintain balance. Strandkvist et al. [32] demonstrated this in patients with chronic obstructive pulmonary disease. Research into the effect of muscle strength in patients with knee joint dysfunction on balance was also conducted in [33, 34].

The problem of comparing our results with those of other authors also stems from the fact that the authors cited above mainly studied patients with an anterior cruciate ligament inju-

ry or unilateral knee joint injury, or without pain. Patellar instability patients have been struggling with dysfunction across the patellofemoral joint for longer than others [35], pain is a significant limitation and the problem usually affects both knee joints. Observing the trend shown in our work, where the patient needs to use more total energy to maintain balance (Fig. 5) over a period of at least 6 months, it is worth referring to the recent study [36]. The authors showed that more postural sway was observed in patients (11 ± 5 days preoperatively) compared to the healthy controls ($p < 0.01$) but 374 ± 23 days postoperatively postural sway between the patients and control subjects was comparable ($p > 0.05$). These results are in line with the current concept of prolonging rehabilitation and monitoring of patients after ligamentous knee surgery. It can therefore be concluded that after ligamentous surgery of the knee joint (ACL, MPFL), there is a real need to extend the rehabilitation process, in terms of training and monitoring, for longer than 6 months [37].

The second aim of the work was to test the discriminative capabilities of the signal from the baroresistive platform. The high values of the ICC coefficients presented in Table 2 demonstrate the high repeatability of the static measurements. The repeatability of these measurements decreased slightly as a function of load. The results also indicate the presence of excited oscillations of the platform. The energy ratios of these oscillations in the three frequency bands analysed differ from those obtained for the dynamic tests. The ratio of the average total energy for the three static tests (20, 50, 80 kg) to the average energy of the signal from all dynamic tests was 0.05, 0.06 and 0.08, respectively. This means that the vibrations of the baroresistive platform had little effect on the dynamic measurements.

In summarising the results of the tests carried out, it is important to mention the limitations that may have affected the quality of the results obtained. The first of these limitations was the method of calculating the signal energy in an arbitrarily defined region in the time-frequency plane. Our attempt to eliminate boundary effects immanent in wavelet analysis resulted in approximately 85% of the total signal energy being included in the calculations. The very nature of the signal analysed should be considered the second limitation. This is because the time trajectory of the loading on the rearfoot depends on the initial conditions, i.e. the lean and velocity of the body at the start of the measurement, and has a more random course compared to the COP trajectory.

Conclusions

Patellar instability patients show greater energy expenditure to maintain body balance and may have an increased contribution of vestibular control.

Our results suggest an extended rehabilitation period for patients after MPFL reconstruction beyond 6 months.

The spectral analysis of the time series of ground reactions measured with the baroresistive platform may give discriminating results for the groups studied. However, a precise numerical pre-processing of the empirical data is necessary. Our results appear to be a contribution to further research in this area.

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