Examinations of bone density changes in selected knee bone ends were evaluated prospectively in a randomized group of 28 patients, aged from 41 to 65 (mean: 55.3 years), who had varus deformations of their mechanic limb axes, mean 8 degrees. The examinations were conducted during the preoperative period, 10 days, 3, 6, and 12 weeks, as well as 6 and 12 months after the procedure. A statistically significant increase in bone density was observed in the medial tibial condyle area, while a statistically insignificant decrease of bone density was noted in the medial femoral condyles. Bone density increased in the lateral tibial condyle area, whereas there were no density changes in the area of the lateral femoral condyles. The research results demonstrate that the relief achieved in ailments after high tibial osteotomies does not directly correspond to the bone density of the affected areas.

Keywords: bone density, gonarthrosis, osteotomy, limb axis, load distribution

Knee osteoarthritis is the most frequent cause of pain and impaired performance in subjects above 65 years of age (Cooper, 1998; Issa & Sharma, 2006). Osteoarthritis develops as a result of genetic predispositions, trauma, local biochemical abnormalities, age-related impairment of cartilage extracellular matrix component regeneration processes occurs, or mechanical overload in overweight subjects (Davis et al., 1988; Anderson & Felson, 1988; Cooper et al., 2000; Hinman & Crossley, 2007; Cooper et al., 1994; Lindsey et al., 2004; Wada et al., 2001). Radiological articular slit is accordingly reduced, leading to a loss of physiological valgus deviation of the knee and development of a varus deviation. Densitometry of articular extremities within the knee shows increased bone mineral density of the medial compartment (Dieppe et al., 1993).

Limb axis correction using high tibial osteotomy (HTO) is one recognized treatment method for early osteoarthritis of the knee joint medial compartment (Wright et al., 2005). Shifting the knee loading axis in the direction of the lateral compartment leads to a remodeling of osseous extremities of the joint (Hurwitz et al., 1998; Thorp et al., 2006). Densitometry may be used for the assessment of bone mineral density within articular bone extremities of the knee, after appropriate limb positioning during the study (Clarke et al., 2004; Cullum et al., 1989; Bohr & Schaadt, 1987). During densitometry, one should therefore expect a decreased bone mineral density within the medial compartment and an increased bone mineral density on the lateral side.

The objective of the study was to assess the affect of limb mechanical axis correction using high tibial osteotomy on the bone mineral density parameters of selected areas of the tibia and femur upon DXA examination (dual-energy X-ray absorptiometry) in comparison with knees not operated on.

Methods

The study involved a prospective assessment of a randomized group of 28 patients (25 women and 3 men) with isolated primary osteoarthritic lesions of the medial compartment of the knee joint. After determining inclusion and exclusion criteria and study method, a random selection of patients has been performed among those qualified at the outpatient department for elective surgical treatment. All patients qualified for the study have given their informed consent for the conduct of the study; the bioethics committee has approved the evaluation program, according to Good Clinical Practice criteria. The patients’ age ranged from 41 through 65 years (55.3 years on average). The study included patients with limb varus malalignment inferior to 10°, in patients that are younger than 65 years old. The patients’ average body weight was 76.5 ± 13.3 kg, and the average body mass index (BMI) was 28.6 ± 3.8 kg/m². These average body weights and BMI values did not vary throughout the observation.
period. Radiological staging of degenerative lesions of the knee was performed based on radiograms taken in an anterior-posterior projection, in a standing position, and using the Ahlbäck classification (Ahlbäck, 1968). Seven patients were diagnosed with stage II osteoarthritis, 12 patients had stage III, while stage IV was observed in 9 subjects. Knee varus malalignment, as measured by the femoral-tibial angle, ranged from 5 to 10° (8° on average).

Before elective surgery, all patients underwent bone mineral density examination (DXA) of four areas within both knees, using a Hologic QDR-4500A densitometer. Before each study, the device was calibrated using a standardized anatomical model. Preoperative and postoperative follow-up examinations were performed, using identical methods of determination of analyzed regions of interest (ROI) and device calibration. Two experienced physicians performed measurements in each patient.

We have obtained both knees scans of a length of 15.019 cm and width of 11.357 cm, with a 0.112 × 0.0563 cm resolution. The analysis involved areas of 80 × 250 pixels. The assessed sections determined surfaces of 0.82 cm² (11 × 11 pixels) of both tibial condyles (ROI1-MTC and ROI3-LTC) and femoral condyles (ROI2-MFC and ROI4-LFC). To precisely and reproducibly determine the location of determined areas, a line was drawn, parallel to the femoral intercondylar line passing through the highest point of the femoral intercondylar groove. The ROI2 area was located 15 pixels below that line, at even distance from the medial and lateral edges of the medial condyle of the femur. A similar method was used to determine the ROI4 area on the lateral condyle of the femur. ROI1 and ROI3 areas were located 3 pixels below the edge of the tibial plateau and 3 pixels eccentrically from the closest intercondylar tubercle (Figure 1). Bone mineral density (BMD) was expressed as g/cm². When analyzing density of various areas, m/l tibia and m/l femur ratios have been additionally introduced, with values corresponding to the ratios of mean bone mineral density of the medial condyle and lateral condyle of the tibia and femur (Wada et al., 2001).

Surgery in all patients began with a diagnostic arthroscopy of the knee. Following arthroscopy, mechanical axis of the limb was being corrected using open-wedge high tibial osteotomy (OW-HTO). The correction angle to a value of 4°–6° valgus femoral-tibial angle was calculated before surgery. All measurements and corrections were performed based on anterior-posterior stature radiograms of the entire limb, taken in an upright position (Paley & Tetsworth, 1992). The dilation space at the osteotomy site was filled with allogenic frozen grafts of trabecular bone. Grafts had the appearance of cubes with a side length of 4–5 mm. During implantation, subsequent fragments were compressed in such a way as to tightly fill the osteotomy wedge space produced. Figure 1 shows the ROI location with respect to the bone grafts filling site. All patients underwent the exact same pattern of postoperative rehabilitation. Passive and aided knee movement was commenced, upon the effects of anesthesia having subsided. Verticalization and walking with elbow crutches with ground contact of the operated foot were initiated, beginning on the 3rd or 4th postoperative day. Loading of the operated limb with up to 20% of normal load was recommended for 3 months, until radiological confirmation of bone remodeling within grafts at the osteotomy site. Verification of compliance with this recommendation was, of course, based on information provided by the patients themselves. Full loading was resumed 3 months following surgery.

In the postoperative period, densitometry scans were performed 10 days following surgery. Studies were then repeated at 3, 6, and 12 weeks, and at 6 and 12 months following surgery. Bone density alterations within both hips and lumbosacral spine were also measured during the above-mentioned examinations; however, their analysis exceeds the scope of the present paper. Standing stature radiographs of lower limbs have also been performed at 3, 6, 9 and 12 months after surgery, to evaluate the permanence of the correction achieved. In a one-year observation, no alterations of the mechanical axis of the operated limb have been observed. A Shapiro–Wilk test has been used to test for the distribution normality of densitometry results. For purposes of confirming statistical significance of differences between study results, the Student t test has been used for dependent variables, together with the ANOVA Friedman test. Statistical correlation of densitometry study results and impact of the size of the correction angle onto the difference in

Figure 1 — The standardized way of the four regions of interest localization.
bone mineral density of selected areas during a one-year observation period were assessed using Pearson’s linear correlation coefficient. The dependence of the results on radiological osteoarthritis staging was assessed via the Kruskal–Wallis test. Result significance was set at $p \leq .05$.

**Results**

Mechanical axes of the knees were corrected using high tibial osteotomy from an average varus malalignment of 8° to an average 5° valgus alignment, using Puddu plates of sizes ranging from 9.0 through 17.5 mm (median, 12.5 mm).

The average bone mass density of the entire area of treated knees, in a one-year observation, was $0.949 \pm 0.15$ g/cm$^2$. One year following surgery, this value increased, as compared with the baseline evaluation, by 0.123 g/cm$^2$.

In the first postoperative study, we observed a substantial increase in knee bone mineral density by 0.185 g/cm$^2$ ($t = –5.084; p = .000$). Subsequent studies have confirmed a gradual decrease of bone mass density, becoming statistically significant in the period between 6 weeks and 3 months following surgery ($t = 2.655; p = .013$). One may note that average bone mass density of the entire treated knee significantly differs in subsequent densitometric studies ($\chi^2$ANOVA = 53.92; $p = .000$).

The average bone mass density of the entire area of untreated knees during the observation period was $0.774 \pm 0.193$ g/cm$^2$. One year following surgery, this value decreased by 0.06 g/cm$^2$. There were no statistically significant differences between results obtained in subsequent densitometric studies ($\chi^2$ANOVA = 0.7; $p = .994$) (Figure 2).

In a one-year observation, a statistically significant increase in average bone mass density has been observed in the ROI1-MTC area of knees following surgery. Bone mass density increase of this area has already been noted in the first postoperative assessment ($t = –6.601; p = .000$). A substantial decrease in bone mass density of this area has been noted 3 months following surgery, as compared with the study at 6 weeks ($t = 3.434; p = .002$). One year following surgery, increased bone mass density of this area of the knee has been noted again, as compared with the study at 6 months ($t = –3.796; p = .002$). Bone mass density of the corresponding ROI1 area of the untreated knee in the entire observation period did not undergo significant changes ($\chi^2$ANOVA = 11.18; $p = .082$) (Figure 3).

The average bone mass density in the ROI2-MFC area of treated knees showed an insignificant decrease at one year following surgery. At 6 weeks following surgery, a significant decrease of bone density has been noted in this area ($t = 2.63; p = .014$). One year following surgery, bone mass density within the area increased again, as compared with the study at 6 months ($t = 2.249; p = .037$). Average bone mass density of the ROI2 area in the untreated knees significantly increased in the observation period ($t = –2.768; p = .01$). This value temporarily decreased between postoperative weeks 3 and 6 ($t = 2.104; p = .045$), and increased again in the evaluation at three ($t = –2.683; p = .008$) and twelve months following surgery ($t = –2.393; p = .025$) (Figure 4).

In the entire observation period, we have noted a substantial increase of knee bone mineral density of the ROI3-LTC area treated knees ($t = –2.185; p = .039$). Increased density was noted as early as 10 days ($t = –2.936; p = .006$), 3 weeks ($t = –2.18; p = .039$), 6 weeks ($t = –4.037; p = .000$) following surgery. There were no statistically significant differences between average densities in the ROI3 area of untreated knees throughout the observation period ($\chi^2$ANOVA = 6.32; $p = .388$) (Figure 5).

Figure 2 — Bone mass density change in the operated (OK) and nonoperated knees (NK).

Figure 3 — Bone mass density change in the ROI1-MTC area in the operated (OK) and nonoperated knees (NK).
There were no statistically significant differences between results of subsequent densitometric studies of the ROI4-LFC area in both knees, throughout the year (OK—χ²-ANOVA = 2.88; p = .823, NK—χ²-ANOVA = 8.43; p = .207) (Figure 6).

Considering the hypothetical assumptions of an impact of limb axis correction onto bone mineral density changes of knees undergoing surgery, these have been presented as a ratio of average bone mineral density of the medial and lateral condyle of the tibia (m/l tibia) and femur (m/l femur). A decrease of the above-mentioned ratios indicates a decrease in bone mineral density of the medial compartment and/or its increase in the lateral compartment. In the preoperative assessment of operated knees, the average m/l tibia ratio was 1.45 ± 0.428, while at 12 months, it reached a value of 1.99 ± 0.553. Accordingly, the m/l femur ratio before surgery was 1.63 ± 0.594 on average, reaching a value of 1.55 ± 0.66 at 12 months.

During densitometric evaluation, performed 10 days after surgery, a significant increase of the m/l tibia ratio was noted (t = –2.518; p = .019), with a subsequent decrease at 6 weeks (t = 3.344; p = .003) and again an increase at 12 months (t = –2.407; p = .028). The ANOVA test has established the statistical significance of differences between average values of this ratio in subsequent assessments (χ² = 28.34; p = .000). The m/l femur ratio is characterized by similar variability (χ² = 25.87; p = 0.000). In untreated knees, the m/l ratios did not exhibit statistically significant variations (Figures 7 and 8).

A relationship has been demonstrated, between average bone mass density of the ROI1-MTC area in operated

**Figure 4** — Bone mass density change in the ROI2-MFC area in the operated (OK) and nonoperated knees (NK).

**Figure 5** — Bone mass density change in the ROI3-LTC area in the operated (OK) and nonoperated knees (NK).

**Figure 6** — Bone mass density change in the ROI4-LFC area in the operated (OK) and nonoperated knees (NK).
knees at preoperative assessment and staging of radiological degenerative lesions according to the Ahlbäck scale (H = 6.69; p = .035), while bone mass density of the entire area of treated knees does not show such a relationship (H = 1.57; p = .455). Bone mass density of the remaining areas of treated knees does not show such a relationship with Ahlbäck scale staging. The m/l tibia ratio also shows a statistical relationship with the above-mentioned scale (H = 10.17; p = .006).

The size of the correction angle shows a negative correlation with the difference in bone mass density within the ROI2-MFC area of treated knees (r = –0.44, p = .031). The larger angle of correction produces smaller difference in bone mineral density of the selected area of the medial condyle of the femur between the assessments at baseline and one year postoperatively.

**Discussion**

A normal mechanical axis of the lower limb connects the center of the femoral head and the center of the ankle joint, corresponding to the center of the talar dome. In a healthy knee, this axis passes through the center of the joint (Maquet, 1980). Shifting the mechanical axis to the medial side of the knee joint leads to premature deterioration of articular cartilage. The subchondral layer of the bone in an overloaded compartment is subject to osteosclerosis and gradual collapse (Wada et al., 2001; Christensen et al., 1982). In our preoperative assessment, we have shown a close relationship between radiological staging of degenerative lesions of the treated knee and bone mass density of the ROI1-MTC area, and the m/l tibia ratio. With progression of knee osteoarthritis, as assessed on radiograms, the density within the ROI1-MTC area was increasing, as was the m/l tibia ratio. This supports results reported by Wada et al. (2001), Clarke et al. (2004), and Lo et al. (2006). There is a positive correlation between bone mass density of the ROI1-MTC and ROI2-MFC areas, representing the medial compartment (r = .567; p = .002) and between the ROI1-MTC area and bone mineral density of the entire knee under assessment (r = .474; p = .011). The angle of varus malalignment in the evaluated group of patients did not correlate with bone mineral density of assessed areas and entire knee.

Increased average bone mass density of knees following surgery at first postoperative densitometric assessment is probably related to the use of impacted, frozen allogenic osseous grafts for the filling of the high tibial osteotomy site. One also needs to consider the impact of surgical technique. The use of osteotomes and wedge dilator may lead to the observed increased bone density by compressing trabecular bone. Subsequent postoperative studies have shown a similar, gradual decrease in bone mineral density of both knees, by the average bone mineral density of the treated knee proved to be substantially superior to the average bone mineral density of the untreated knee. This decrease is related to the possibility of even load distribution on both limbs, while increased bone mineral density in the treated knee is the result of a slow remodeling of allogenic grafts and callus formation, thus resulting in increased BMD.

In a 3-month observation of patients following surgical correction of limb mechanical axis, a gradual decrease of the m/l tibia ratio has been shown, related to the decreased bone mineral density of the ROI1-MTC area, and increased density within the ROI3-LTC area of treated knees. In the same observation period, a similar change may be seen in this respect in terms of m/l femur ratio and bone mineral density in the ROI2-MFC area. This change may be connected with a shifting of load to the lateral side of the knee following high tibial osteotomy and, according to the Wolff rule, may lead to a slow osseous remodeling of articular bony ends of the knee joint (Kawakami et al., 2005; Akamatsu et al.,

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**Figure 7** — Bone mass density change in condyles of the tibia (m/l tibia) and femur (m/l femur) in the treated limb.

**Figure 8** — Bone mass density change in condyles of the tibia (m/l tibia) and femur (m/l femur) in the untreated limb.
This partially supports the results obtained by Koshino and Ranawat, who have demonstrated that at one year following corrective surgical tibial osteotomy, a substantial decrease in strontium-85 uptake is noted in the medial condyle of the femur (Koshino & Ranawat, 1972). Results of subsequent densitometric evaluations at 6 and 12 months following surgery are surprising, showing a significant, repeated increase in bone mineral density of the ROI1-MTC and ROI2-MFC areas, as well as m/l tibia and m/l femur ratios. Bone mineral density of the subchondral layer of the medial condyle of the tibia at 12 months following surgery was superior to preoperative values. The significant correlation between correction degree and density in the ROI3-LTC area in treated knees m/l tibia ratio value are of additional interest. Based on this correlation, one may assume that the larger the shifting of loads to the side of the lateral condyle of the tibia following osteotomy, the greater the increase in bone mineral density within that area, following surgery. In a one-year observation, the hypothesis of load relief and osseous remodeling of the medial compartment of the involved knee following open-wedge high tibial osteotomy cannot be confirmed. Akamatsu et al. have presented different results in terms of bone mineral density changes of the tibial epiphysis; the authors have observed a gradual decrease in bone mineral density of the medial compartment, and a gradual decrease of the m/l tibia ratio (Akamatsu et al., 1997).

All patients reported a significant decrease in pain, and a significant improvement of the mobility, thus enabling them to increase the load on the limb. Physical activity parameters, as assessed at the end of the study by treated patients themselves, were found to be improved as compared with the preoperative period. Slight limitations were usually the effect of complaints connected with the other, nonoperated knee. The operated limb was found to play a major supportive role.

The studies performed reveal that in a one-year observation, OW-HTO does not provide the expected load relief effect, as expressed by decreased BMD in the medial compartment of the knee. Our patient population was mainly female. Therefore, we cannot be entirely certain of how gender may affect bone tissue remodeling and load distribution following osteotomy. This should be further investigated in a study that includes both genders. Decreased bone mineral density (MTC and MFC values), observed between the 10th postoperative day and 3 months following treatment, are probably related to the unloading of the treated limb through the use of two elbow crutches. Restoration of the “normal” load and walking symmetry leads to an increased bone mineral density within these areas, during the period of 3–12 months after treatment. A separate assessment of the impact of normal walking patterns and loading levels does not appear to be possible; therefore, these two parameters are considered jointly, as a single factor in subsequent studies. In our view, studies of factors that may have an effect on the bone mineral density of treated knees should be considered, extending the observation period, to track potential changes after patients resume normal activities. Load relief may occur, but BMD measurements (which are also dependent upon other factors) do not appear to be the most appropriate criterion for evaluating this load relief. The use of autologous grafts to fill the osteotomy site and a comparison of callus formation, after the use of compacted autologous or allogenic grafts, may also prove useful.

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References


