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Recovery of the Menisci and Articular Cartilage of Runners After Cessation of Exercise

Additional Aspects of In Vivo Investigation Based on 3-Dimensional Magnetic Resonance Imaging

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Background: It is still unclear whether long-distance running has a deleterious effect on joint health; therefore, this study was undertaken to examine the rate of recovery from alterations occurring at the knee joint in marathon runners due to loading.

Hypothesis: Tibial, patellar, and meniscal cartilaginous volumes are able to recover adequately from changes due to repeated loading immediately after cessation.

Study Design: Controlled laboratory study.

Methods: Twenty knees of male athletes were studied (mean age, 38 ± 14 years). The participants ran 20 km around a predetermined and precisely measured course. Cartilaginous volume was measured by magnetic resonance imaging before the run (60-min rest before exercise), immediately after the run (3-min delay), and after a recovery period of 1 hour.

Results: After the 20-km run, there was a significant transient decrease in cartilage volume. After 1 hour of rest, no significant reduction of cartilage volume was measured for the patella (–2.1%), the tibia (–1.2%), the lateral meniscus (–3.2%), or the medial meniscus (–5.9%). However, the values recorded for the menisci were borderline, which indicates that recovery of meniscus volume lags behind that of articular cartilage.

Conclusion: Our data indicate a clear tendency toward rapid recovery of the cartilaginous and meniscal volumes at the knee. The results of this study lead to the assumption that the cartilage and the menisci are well able to adapt to the loads caused by running. Investigation of more subtle changes would require more specific magnetic resonance imaging techniques, including T2-weighted mapping and T1-weighted rho sequences, to assess cartilage biochemistry.

Clinical Relevance: The articular structures were investigated on a general magnetic resonance imaging level and were found to recover rapidly so that exercise could be continued after a short time without reservation.

Keywords: cartilage volume; long-distance running; magnetic resonance imaging (MRI); recovery

Marathon running has become a very popular sport and therefore has also become the focus of scientific interest and medical research. The lower extremities are subjected to a high amount of stress during running so that the likelihood of injury is increased. It is estimated that the impact forces experienced by a runner amount to 2 to 3 times the body weight.[1,27]

The prevalence of injuries associated with the activity of running has compelled sport scientists to investigate the effects it has on body structures.[10,19] As a relatively high percentage of injuries are associated with knee pain, it is important to undertake close analysis of the knee joint, which acts as a shock absorber and is the primary center for the dissipation of energy during running.[2,6]

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The cartilage contributes to ensuring that these enormous forces are transmitted as uniformly as possible from 1 skeletal element to the next. Whether cartilage can achieve this task under such excessive loads as repeated marathon runs and remain intact is still the subject of considerable controversy.[2,4,18,25]

The direct effects of mechanical loading patterns occurring during a marathon run have been reported in an earlier publication.[17] Evaluation of these effects was based on a quantitative analysis (MRI) of the articular cartilage of the knee (tibia and patella) and of the menisci in healthy male athletes. The femoral cartilage was not included in the study because its evaluation is highly complex and the available technology was not adequate to guarantee precise analysis and reproducible results. Data were obtained on volume changes in the tibial and patellar cartilage and the medial and lateral menisci after marathon runs. In addition, it was possible to conclude that individual biometric factors such as age, weight, body mass index (BMI), training hours per week, or previous athletic activity had no statistically significant effect on the extent of volume change. In this article, we report the volume changes after a 1-hour recovery period in relation to the volume directly after completing the run. Recovery times may vary with the age of the athlete, but it is important when giving advice on training schedules to have scientific data available on which to base recommendations.

MATERIALS AND METHODS

Participants

Ten male runners (20 knees) with experience in marathon running were recruited to the study as volunteers from an athletics club. The decision to include men only was intended to eliminate gender-related variables. The runners were screened for good general health and to ensure that they had no knee pain and no known previous joint disorders. They were also asked to sign an informed consent form before participation. They were required to give their agreement in writing to the use of their data for scientific purposes and to confirm that they would undertake the experimental run at their own risk. The runners were aged 26.5 ± 3 years (range, 21-28 years). The average height of the runners was 180 ± 9 cm, average weight 74.5 ± 7.2 kg, BMI 22.8 ± 1.5 kg/cm^2, and were all of normal weight (BMI range, 20.8-24.8).

Training history varied between 20 and 150 km per week (on average, 67.1 ± 35 km/week); there were also differences in the duration of regular physical exercise ranging from 1 to 23 years (average, 8.5 ± 6.5 years). These differences, and the small number of participants, mean that extrapolation of data to the general athletic population would be inappropriate at this stage of investigation.

Study Design

After marathon runners were recruited to the study and an appropriate MRI sequence was selected, the individual data of the runners (eg, age, height, weight, BMI, training experience, and other sports) were collected. The first MRI measurements (M1) of tibial, patellar, and meniscal cartilaginous volumes were taken after a 60-minute rest period during which the runners lay down. The rest period aimed to minimize effects of short-term loading on cartilaginous volume before the run. The runners did no warming up but started straight from the MRI investigation room, running 20 km, and finishing up back in the MRI room. The second measurement (M2) was made directly after the run with a negligible delay of no more than 3 minutes for positioning the runner and adjustment of the tomograph. The third measurement (M3) was made after 60 minutes of recovery, whereby each runner lay on the MRI bed and rested for 1 hour. The MRI datasets were then transferred to a computer and the tibial, patellar, and meniscal cartilaginous volumes were visualized as 3-dimensional reconstructions.

Image Acquisition and Analysis

Each runner was centered in the supine position and entered the magnetic resonance tomograph feet first. The device used in this study to obtain images of the knee joint (Magnetom Symphony, Siemens, Erlangen, Germany) has a field strength of 1.5 T, a circular-polarized extremity coil, a fast low-angle shot sequence, and 3-dimensional water excitation technique: repetition time, 19.2 ms; echo time, 9.5 ms; fractional anisotropy = 30°; resolution, 0.31×0.31 mm^2; field of view, 16 cm; matrix = 512^2 pixels. There were 64 sections taken in sagittal series with a section thickness of 1.5 mm.

To ensure blinding for the image processing procedure, the MRI datasets were coded and transferred to a computer system (Octane Duo, Silicon Graphics, Mountain View, Calif). Volume measurement was performed semi-automatically; that is, the cartilaginous surface was marked layer by layer by hand, but the cartilage-bone margin was determined automatically with the possibility of manual correction. After this measurement had been performed for each cartilage (and/or meniscus) for all layers, the volume and thickness of the cartilage were calculated by means of a 3-dimensional reconstruction based on isotropic voxels. Repeated measurements involving repositioning of the joint yielded a coefficient of variation of 0.95%.[7,8]

Statistical Analysis

The Wilcoxon matched pairs rank test for differences was used to test the percentage volume changes for the tibial, patellar, and meniscal cartilaginous volumes for statistical significance in comparison with initial values. Both knees of the same runner were examined and treated independently in the statistical analysis. Level of significance was set at $\alpha = 95\%$, corresponding to $P = .05$.

RESULTS

Behavior of the Cartilage and Meniscus Volume After 1 Hour of Recovery

Patellar Cartilage. The volume of the patella, which had decreased by an average of –7.0% (M1-M2), was measured again after a 1-hour recovery period (M3). At this point, the

TABLE 1
Volume Changes After Loading and Cessation of Exercise[a]

	Decreased Volume After 20-km Run (M2 vs M1)	Increased Volume After 60-min Recovery Period (M3 vs M2)	Reduced Volume After 60-min Rest Period Compared to Status Before Running (M3 vs M1)
Patella	–7.0% (*P* = .002[b])	5.3% (*P* = .002[b])	–2.1% (*P* = .16)
Tibia	–5.1% (*P* = .02[b])	4.3% (*P* = .048[b])	–1.2% (*P* = .44)
Medial meniscus	–8.2% (*P* = .003[b])	2.7% (*P* = .035[b])	–5.9% (*P* = .055)
Lateral meniscus	–9.3% (*P* = .007[b])	6.8% (*P* = .01[b])	–3.2% (*P* = .054)

[a]The reduction in volume is given as a percentage reduction of the initial volume after 20 km runs and after cessation of exercise. Overall there were significant reductions in volume after loading and no significant reduction after 1-hour recovery.
[b]Significantly different ($P < .05$).

cartilage volume had increased again by a significant +5.3% (*P* = .002) and therefore was now only –2.1% less than the first measurement (M1). When testing for significance, *P* was equal to .16, indicating that the volume value after the recovery period (M3) showed no significant difference to the volume value before loading (M1) (Table 1; Figure 1).

Tibial Cartilage. The subjects showed an average volume reduction of –5.1% after the 20 km run; after an hour, this had already recovered by +4.3%. Therefore, there was a cartilage reduction of 1.2% an hour after the run as compared with the resting measurement before the run. When testing for significance, *P* was equal to .44, indicating that the volume value after the recovery period (M3) showed no significant difference to the volume value before loading (M1) (Table 1, Figure 1).

Menisci. After a volume reduction of –8.2% in the medial meniscus, the volume had increased again by 2.7% after an hour and was therefore –5.9% lower than the resting measurement (*P* = .05). The lateral meniscus showed a change of –9.3% immediately after the run and gained +6.8% in volume during 1-hour recovery. Therefore, there was a cartilage reduction of –3.2% ($P < .04$) 1 hour after the run as compared with before the run. This means that the volume value for the medial and lateral meniscus after the recovery period (M3) showed no significant difference to the volume value before loading (M1), although values for the menisci were borderline, indicating that these structures had not fully recovered after 1 hour (Table 1, Figure 1).

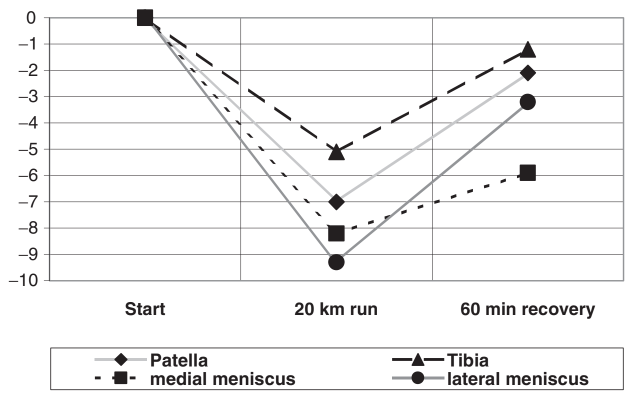

Figure 1. The volumes of the patella, tibia, medial and lateral menisci were measured before the start of a marathon run of 20 km, and after 60 minutes of recovery. In all areas, a significant volume reduction could be observed after 20 km. Although there was a tendency to lower volumes, values from cessation of exercise to 60 minutes recovery were only significant between data before running and after running.

DISCUSSION

Changes in the volume and thickness of knee joint cartilage have been investigated in numerous studies. Clinical measurements have been obtained for healthy and disordered knees[5,12,16] and in different loading situations.[14,21] However, neither the relationship of changes to loading nor behavior patterns during or after recovery have been investigated so that conclusions on knee cartilage changes as an individual risk factor for degenerative joint disease must be called into question.

Analysis of volume changes after an hour of rest following a 20-km run revealed a significant increase toward the initial value in the tibial, patellar, and lateral meniscal cartilaginous volumes reduced by exercise. Based on the results of the present study, the articular cartilage (tibial and patellar) recovered more fully in terms of its volume than was the case for the menisci after subjection to sustained dynamic loading.

Structurally, joint cartilage is hyaline cartilage consisting of a small percentage (1%-10%) of chondrocytes and a large percentage of water (70%-80%), and has a matrix of collagen (type II 10%-12%) and proteoglycan molecules (7%-9%).[22]

The avascular joint cartilage is nourished almost exclusively by diffusion from the synovial fluid. Cell physiological study of cell cultures has revealed an increased synthesis rate for chondrocytes after dynamic loading, whereas metabolic inhibition is recorded for purely static compression.[3,24,26] A progressive loss of cartilage volume of up to 25% has been observed after immobilization of the human knee joint in paraplegics.[28] In contrast, no significant changes are apparent in a healthy patient with continuous extreme loading of the knee. Mühlbauer et al[21] compared highly trained male triathlon athletes with a nonathletic group (<1 hour of sport per week) and found no significant differences in cartilage thickness.

The menisci consist structurally of fibrous cartilage that is formed from water (74%) and cells and the extracellular matrix they produce. This matrix varies across the various zones of loading: At sites of greater tensile load, the meniscus is fibrous in character with a high dermatan sulfate content; at sites of greater compression load, it has a hyaline structure and more chondroitin sulfate. The dry matter of the meniscus consists of 75% collagen, 8% to 13% other proteins, and about 1% hexosamines.[20] In articular cartilage, collagen type II predominates, whereas the menisci are dominated by collagen type I. On the other hand, the proportion of proteoglycans constantly decreases, from an initial 20% to about 10% by age 60 years. The ability of the meniscus to maintain its shape is provided by the protein elastin; however, this accounts for only 0.6% of the total collagen.[13]

The meniscus, like joint cartilage, shows a viscoelastic reaction to loading. The intrinsic viscoelastic properties of the macromolecules play a role in this load-dependent deformation as do fluid fluctuations through the porous matrix.[11] In experimental studies of compressed menisci, an elasticity module has been found that is only about half the size of that of the hyaline joint cartilage and permeability was found to be only one-sixth to one-tenth.[20]

These findings support our results and show that the menisci with their minimal elasticity and permeability as well as their far greater coherent mass compared with articular cartilage are well suited to their function as shock absorbers and for the task of distributing applied forces uniformly across the articular surface. This may also explain why recovery of meniscus volume lagged behind that of the other structures under investigation.

The residual volume reductions after a 1-hour rest period must be strictly differentiated from reductions due to atrophy. In the study by Hinterwimmer et al,[14] clear reductions in the tibial and patellar cartilaginous volumes were observed after 7 weeks of immobilization, but this is an alteration of a different origin for which the rates of recovery have not yet been investigated. In a study by Eckstein et al,[9] the recovery of the patellar cartilage after mechanical loading in the form of 100 knee bends was investigated. The rate of volume change, measured as "fluid flux" (flow per surface unit), showed a linear progression in the time period after the physical activity. In addition, a high correlation between this rate of volume change and the size of the deformation was observed; this means that individuals with a greater cartilage deformation also showed a more rapid resorption of fluid after loading. Eckstein et al stated that the initial cartilaginous volume had not yet been restored after a 90-minute rest period. These effects were not observed in our investigation and, therefore, we must refute them. The differences between these contradictory statements can be explained with reference to the statistical analysis. Sixty minutes after the end of exercise, Eckstein's graph shows –2.0% volume change compared with the status after physical rest. We were able to confirm this value in our investigation (–2.1% reduced volume after 60-minute rest period compared with status before running) and to establish that it is statistically not significant (P = .16). In the study by Eckstein et al, statistical significance was not reported but rather the results and the far lower value of 1.0% after 90 minutes were summarized as "the cartilage required more than 90 minutes to recover from loading."

Identical study protocols were used for both studies. The main difference between them is to be found in the areas under investigation. Eckstein et al only examined the behavior of the patellar cartilage, whereas our study looked at the menisci and the tibial cartilage. Eckstein et al studied 7 patients, of whom 3 were women (43%). In contrast, we studied 10 patients, all of whom were men, thus eliminating gender-related variables such as hormonal effects. Furthermore, Eckstein et al carried out 2 different load cycles. First, after a period of rest, the patients performed knee bends every 15 minutes and volume changes were measured immediately after each load cycle. After the first load cycle (50 knee bends), there was a statistically significant reduction in the volume of the patellar cartilage from 2.4% to 8.6%. Further load cycles did not cause any additional reduction in patellar cartilage volume so that the level remained at about 6% below that at physical rest. This corresponds to the values of –7% decreased volume after a 20-km run recorded in our study. However, the menisci, which were not evaluated by Eckstein et al, showed greater volume reduction after loading (medial –8.2%, lateral –9.3%) than the volumes recorded for the patella (–7.0%) or tibia (–5.1%).

In a second experiment, Eckstein et al investigated recovery changes after 1×100 knee bends. The first measurement taken immediately after loading (3-7 minutes) revealed a reduction in patellar cartilage volume of –5.0%. In our study, we recorded a value of –7.0%. The difference can be attributed, in our opinion, to the far higher load levels (20 km run vs 100 knee bends) sustained by our participants. Eckstein et al found a residual volume reduction of only –2.0% (% volume change) after a rest period of 60 minutes. We recorded the same values in our investigation (–2.1% reduced volume after a 60-minute rest period compared with prerunning status). This suggests the assumption that rapid recovery of up to –2% of the initial value can be expected after the first hour of rest even after excessive loading that has caused a marked reduction in cartilage volume.

It seems that the recovery of volume is a slow process. Rubenstein et al[23] concluded from their compression-testing study on bovine cartilage that deformation of cartilage during loading (in this study, approximately 4 MPa) occurs more readily than restoration in the recovery phase.

Hohmann et al[15] assert in their study that external impact loading in long-distance running does not create internal stress on bone and cartilage that is demonstrable on MRI. They state that the anatomical structures are so well developed that they prevent volume changes from occurring. The results of our study refute this assertion. We found a significant reduction after running even moderate distances, as reported in a previous article.[17] We also found an increase in recovery volume after 60 minutes; that is, changes in volume were demonstrable in the anatomical areas we investigated. In agreement with the research led by Eckstein and Rubenstein and their colleagues, as mentioned above, we found that not all cartilaginous volumes that had diminished during a 20-km run were fully restored after a 1-hour rest period. Recovery of the medial meniscus lagged behind the other structures. However, our data do not show evidence of pathological changes in relation to the volumes of the cartilage and menisci in the knee joint due to the high propensity for recovery within these structures. In our study, a heterogeneous group of male volunteers from an athletics club was investigated. A deliberate decision was made not to divide the participants into subgroups in an attempt to link volume reduction to range of training and physical exercise history or to personal factors such as age or BMI because the number of persons in each group would have been too small and statistical validity would have been jeopardized.

On the basis of the results reported here, we assume that the cartilage is able to adapt well to loads caused by running and has the propensity to recover from changes due to repeated loading after cessation. Nevertheless, more data need to be collected from a larger cohort and more extensive and detailed examination of structures is required before an authoritative statement on recovery of cartilage and meniscal volumes after exercise can be provided. In particular, it remains to be determined when and whether the menisci recover completely from volume changes caused by exercise.

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