Journal of Athletic Training 2024;59(9):906–914
doi: 10.4085/1062-6050-0659.22

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Morphologic Response in Femoral Cartilage During and After 40-Minute Treadmill Running

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Context: It is unclear whether the response in femoral cartilage to running at different intensities is different.

Objective: To examine the acute patterns of deformation and recovery in femoral cartilage thickness during and after running at different speeds.

Design: Crossover study.

Setting: Laboratory.

Patients or Other Participants: A total of 17 healthy men (age = 23.9 ± 2.3 years, height = 173.1 ± 5.5 cm, mass = 73.9 ± 8.0 kg).

Intervention(s): Participants performed a 40-minute treadmill run at speeds of 7.5 and 8.5 km/h.

Main Outcome Measure(s): Ultrasonographic images of femoral cartilage thickness (intercondylar, lateral condyle, and medial condyle) were obtained every 5 minutes during the experiment (40 minutes of running followed by a 60-minute recovery period) at each session. Data were analyzed using analysis of variance and Bonferroni- and Dunnett-adjusted post hoc *t* tests. To identify patterns of cartilage response, we extracted principal components (PCs) from the cartilage-thickness data using PC analysis, and PC scores were analyzed using *t* tests.

Results: Regardless of time, femoral cartilage thicknesses were greater for the 8.5-km/h run than the 7.5-km/h run (intercondylar: $F_{1,656} = 24.73$, $P < .001$, effect size, 0.15; lateral condyle: $F_{1,649} = 16.60$, $P < .001$, effect size, 0.16; medial condyle: $F_{1,649} = 16.55$, $P < .001$, effect size, 0.12). We observed a time effect in intercondylar thickness ($F_{20,656} = 2.15$, $P = .003$), but the Dunnett-adjusted post hoc *t* test revealed that none of the time point values differed from the baseline value ($P > .38$ for all comparisons). Although the PC1 and PC2 captured the magnitudes of cartilage thickness and time shift (eg, earlier versus later response), respectively, *t* tests showed that the PC scores were not different between 7.5 and 8.5 km/h (intercondylar: $P \geq .32$; lateral condyle: $P \geq .78$; medial condyle: $P \geq .16$).

Conclusions: Although the 40-minute treadmill run with different speeds produced different levels of fatigue, morphologic differences (<3%) in the femoral cartilage at both speeds seemed to be negligible.

Key Words: acute cartilage response, ultrasonography, treadmill run, thickness

Key Points

- Treadmill running at constant speeds of 7.5 and 8.5 km/h produced different levels of physiological and psychological fatigue.
- Running at speeds of 7.5 and 8.5 km/h did not seem to change femoral cartilage thickness.
- Femoral cartilage thickness between 2 running speeds were different, but the magnitudes were small (effect size ≤ 0.16).

Physical activity with continuous weightbearing exerts a mechanical load on a joint, which can lead to acute deformation in the articular cartilage.[1] After the load is removed, the articular cartilage regains its former thickness.[2] Given that quantifying deformation in articular cartilage after physical activity is important in understanding the responding pattern, femoral cartilage thickness has been evaluated using ultrasonography.[3–5] For example, researchers have reported that the same duration of walking and 2-legged landing result in a 7% and 10% reduction, respectively, in the medial condyle thickness and that lateral and medial condyle thickness after 30 minutes of running and 2-legged landings do not differ.[3,5] Taken together, the acute change in femoral cartilage deformation seems to be greater after running or landing than walking, and the degree of morphologic deformation appears to be associated with the magnitude of mechanical load exertion to the joint and the cartilage.

The health benefits of physical activity are obvious, but such activity also exerts a mechanical load on cartilage.[6] As a long-term consequence, the accumulation of exercise-induced mechanical stress could lead to a pathological condition such as chondrosis; therefore, the rate of recovery (eg, restoration of normal thickness) of cartilage thickness after physical activity is another important factor regarding the acute deformation and long-term health of articular cartilage.[7] Among anatomic structures of the knee joint, femoral cartilage could be associated with specific types of knee pathology (medial condyle: anterior cruciate ligament reconstruction; lateral condyle: patellofemoral pain) and alignment (medial condyle: varus knees; lateral condyle: valgus knees).[8–10] Therefore, the observation of an acute morphologic response (eg, deformation and recovery) in femoral cartilage, such as the intercondylar, lateral condyle, and medial condyle thickness, according to exercise would provide fundamental data on healthy cartilage biomechanics.

Although available data on knee-joint cartilage thickness associated with exercise are valuable, some of these data are the results of tibial cartilage, and the data on the recovery time (>45 minutes; >30 minutes) of exercise-induced femoral cartilage deformation are confounded by variations in exercise types.[3,8,11–14] Information on the timing of changes in cartilage thickness and the time required for recovery according to exercise intensity could be used for exercise guidelines and recovery strategies for joint health. Running is one of the most frequently performed exercises. Data on morphologic changes in femoral cartilage according to running duration do exist, but recovery characteristics according to running intensity are relatively unclear.[15] Comparing the effects of 2 different running speeds with repeated measures (eg, every 5 minutes) on cartilage thickness during and after exercise would allow us to assess the patterns of deformation and recovery. Based on pilot work in which we assessed blood lactate concentration (BLC) and the rate of perceived exertion (RPE), we believe treadmill belt speeds between 7.5 and 8.5 km/h could provide distinct running intensities.

Therefore, the purpose of our study was to examine the acute response of femoral cartilage thickness during and after treadmill running at 7.5 and 8.5 km/h. The results of our study will provide a better understanding of deformation and recovery patterns at the given running speeds. In our assumption based on the previous data, individuals running at different speeds would have to exert different mechanical loads; thus, we hypothesized that an exercise-induced acute deformation would be larger, occur earlier, or both in participants running at a speed of 8.5 km/h compared with those running at 7.5 km/h and that participants running at a speed of 8.5 km/h would show a slower recovery rate than those running at 7.5 km/h.[16]

METHODS

Design

We used a repeated-measures design in which the thicknesses of the femoral cartilage were measured every 5 minutes during the entire experiment (40 minutes of treadmill running followed by a 60-minute recovery period). Treadmill running at 7.5 or 8.5 km/h was performed during 2 separate sessions with a 48-hour break between sessions. Independent variables were condition (treadmill belt speed of 7.5 or 8.5 km/h) and time (every 5 minutes throughout the experiment). In addition, to compare the workload between 2 running speeds, we assessed step count, BLC, and the RPE. Specifically, step count was recorded to quantify activity levels, and the BLC and RPE were obtained to estimate the levels of physiological and psychological fatigue, respectively.

Participants

Initially, 18 healthy young men who were physically active (ie, exercising at a moderate intensity of >150 min/wk) volunteered to participate, but 1 was unable to complete the treadmill run; thus, a total of 17 participants (age = 23.9 ± 2.3 years, height = 173.1 ± 5.5 cm, mass = 73.9 ± 8.0 kg) were analyzed. Included participants had no lower extremity injury within the 6 months before the study or any lower extremity surgery in their lifetime. Volunteers were excluded if they had metabolic or cardiovascular diseases. All participants provided written informed consent, and the study was approved by our university's institutional review board.

Procedures

Upon arrival at the laboratory for their first visit, participants read the testing procedures. To unload the femoral cartilage, they sat on a plinth with their knees fully extended for 30 minutes on a treatment table.[5] At the end of the 30-minute rest, pre-exercise assessments of ultrasonographic images of femoral cartilage, step count, BLC, and the RPE were acquired.

Participants then performed 1 of the 2 running protocols (a constant belt speed of 7.5 or 8.5 km/h with an incline of 1°) on a treadmill (Jog Forma; Technogym). The order of running speed was determined by flipping a coin at the first visit. The running protocols had to meet important criteria. First, the duration of running had to be not only long enough to observe the acute deformation in femoral cartilage but also completable by participants. Although a minimum of 30 minutes of aerobic exercise is recommended, we thought that an additional 10 minutes of running could allow us to observe the acute deformation pattern of femoral cartilage; thus, the duration of running was set as 40 minutes.[17] Second, the 2 running intensities (differentiated by the treadmill belt speeds) had to be physiologically and psychologically distinctive. In previous research, treadmill belt speeds of 5.4, 7.2, and 9.0 km/h resulted in different plantar pressures.[18] Using these previous data, we determined the treadmill running speeds via our pilot work (n = 4 treadmill speeds): speed < 7.0 km/h was not a high enough intensity for running, and our population of recreationally active healthy individuals was unable to complete a 40-minute run at a speed of 9 km/h.[18] Every 5 minutes during running, ultrasonographic images of femoral cartilage and step count were recorded (Figure 1). This assessment during running took approximately 1 minute; thus, treadmill running included 8 additional 1-minute assessment periods, which yielded a total running protocol time of 48 minutes.

After completing treadmill running, participants moved to the treatment table and rested for 60 minutes in the same position as during pre-exercise unloading. During this postexercise period, ultrasonographic images were recorded every 5 minutes. The postexercise assessment of BLC and RPE were also measured.

Outcome Measures

Ultrasonographic images of femoral cartilage were obtained in the *dominant limb*, which was defined as the self-reported limb preferred for kicking a ball.[19] All participants were right-foot dominant. We asked participants to sit against the wall and flex their dominant knee to 140° (confirmed using a plastic goniometer; Figure 2A). To minimize the measurement time (1 minute) and the number of steps,

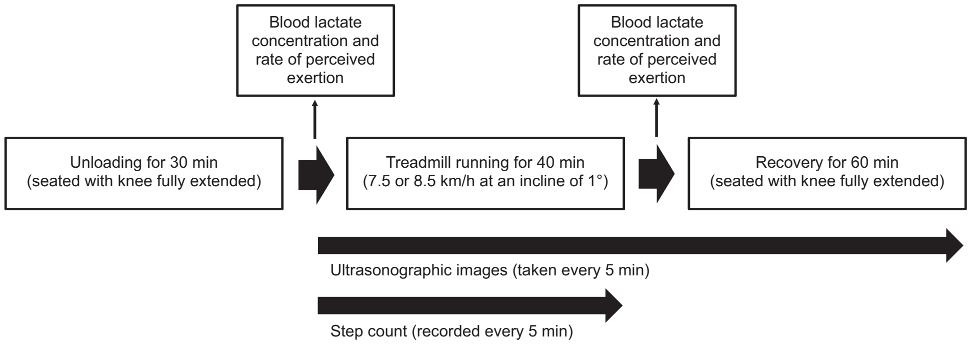

Figure 1. Testing procedures.

we installed the treatment table near the treadmill (<5 steps). A measuring tape was attached to the treatment table in front of the participant's big toe and was used to record the distance between the wall and tape for the subsequent measurements. Using ultrasound (US) imaging devices (Ecube-i7; Ecube-12) equipped with a 12-MHz linear transducer, we captured femoral cartilage images. Interdevice reliability on these devices was calculated as an intraclass correlation coefficient (ICC) of 0.96. Specifically, the transducer was placed transversely at the center of the medial and lateral femoral condyles above the superior edge of the patella and rotated in the sagittal plane to maximize the reflection of the cartilage. Three images were obtained for each time point. Recorded US images were exported to ImageJ software (version 1.53e; National Institutes of Health) to calculate the thickness values. First, a scale was set according to the image size (19.2 or 15.4 pixels/mm). The thickness (in millimeters) was calculated using a straight line (perpendicular to the cartilage-bone interface) at the midpoint of the upslope of the cartilage (intercondylar thickness) and from the midpoint of the intercondylar notch to the medial (medial condyle thickness) and lateral (lateral condyle thickness) edges of the cartilage interface (Figure 2B).[3,20] After thicknesses were assessed, potential outliers were identified and removed. *Outliers* were defined as the analyzed values exceeding 2.5 SD from the mean value of the corresponding measurements for each condition at each time point.[4] From these filtering methods, <0.1% of the US images in each dependent measurement—112 in thickness (intercondylar: 21; lateral condyle: 54; medial condyle: 37) out of 2142 images—were excluded from final analysis. After removing the outliers, we averaged the remaining values at each time point for statistical analysis. A researcher (J.L.) who was blinded to the intervention and image acquisition performed the whole analysis. The established measurement consistency of this researcher was 0.96 and 0.83 for intrasession and intersession reliability, respectively (3 images of medial condyle thickness acquired at 2 separate sessions with a 48-hour washout period; n = 5).

During the unloading period, an activity tracker (Charge 4; Fitbit) was applied to the left wrist and wirelessly connected to a mobile telephone application to measure step count before and during running.

Blood lactate concentration and the RPE were assessed before and after running. Using a lactic acid concentration meter (lactate meter, Lactate Plus; Nova Biomedical), we collected 0.7 μL of blood from participants' fingertips using a lancet needle (26 gauge; MoaMP Inc) and the test strip (Lactate Plus Lactate Test Strips; Nova Biomedical). The Borg scale for rating of perceived exertion was used to measure the RPE of participants.[21]

Statistical Analysis

A priori power analysis was performed based on our pilot data to determine sample size. Using an α level of .05 and a β level of .20, we estimated that 17 participants were needed to detect a statistical difference between the 2 running speeds in femoral cartilage thickness (mean $\pm$ SD difference of 0.22 $\pm$ 0.32 mm, effect size of 0.69).

To test condition by time interactions and main effects, we performed 6 separate mixed-model analyses of variance (random variable: participant; fixed variables: condition and time) for cartilage thickness (2×21 for intercondylar, lateral condyle, and medial condyle), step count (2×9), BLC (2×2), and RPE (2×2). To control the type I error rate, we performed Bonferroni-adjusted (condition) or

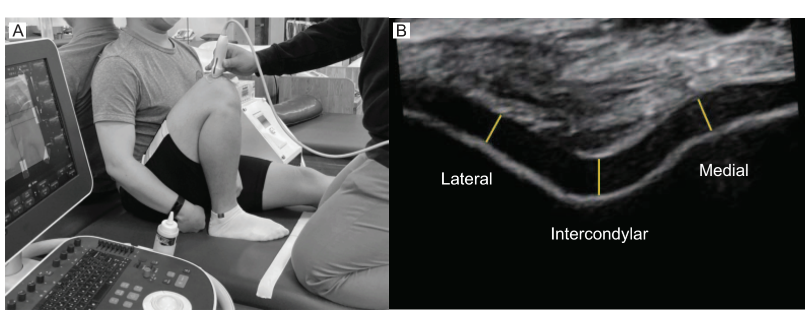

Figure 2. Femoral cartilage measurement. A, Femoral cartilage ultrasound setup and participant positioning. B, Femoral cartilage thickness ultrasonographic outcome measures.

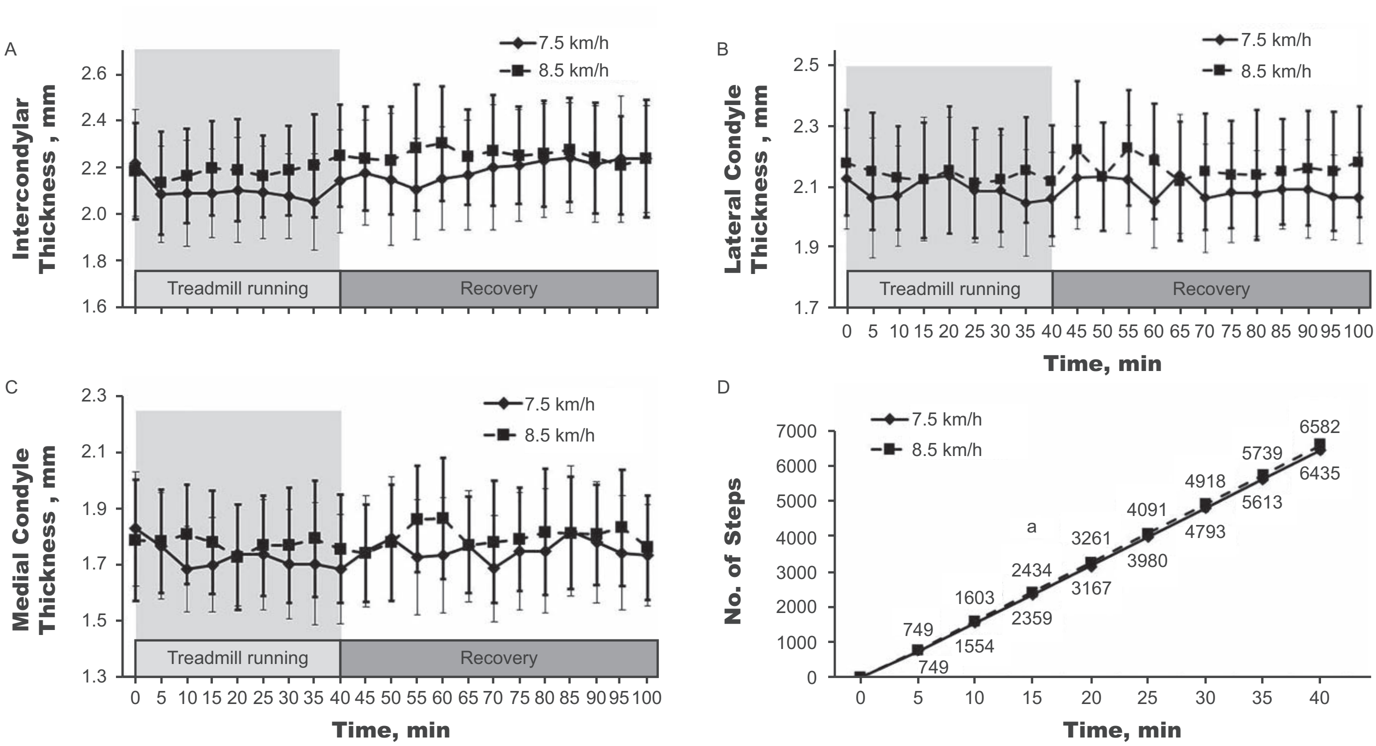

Figure 3. Change in thickness over time. A, Intercondylar thickness (condition × time: $F_{20,656}$ = 0.76, *P* = .77). B, Lateral condyle thickness (condition × time: $F_{20,649}$ = 0.56, *P* = .94). C, Medial condyle thickness (condition × time: $F_{20,655}$ = 0.84, *P* = .66). D, Change in step count over time (condition × time: $F_{8,272}$ = 2.10, *P* = .04). Values are means and 95% CIs. The values below and above the lines are steps counted for the condition of 7.5 and 8.5 km/h, respectively. [a] Differences between conditions from 15 to 40 minutes (*P* ≤ .03, d ≤ .73).

Dunnett-adjusted (time main effect) *t* tests for post hoc comparisons.[22] Specifically, a Bonferroni adjustment was determined by the number of comparisons ($P = .05/40 = .001$). Dunnett tests were performed to examine the specific differences in the values at baseline and other time points using the modified *t* statistic ($P < .05$). To determine practical significance, we also calculated effect sizes ($d = [\overline{X}_1 - \overline{X}_2]/\sigma_{pooled}$) and interpreted them as *small* ($d < 0.2$), *medium* ($0.2 \leq d \leq 0.8$), and *large* ($d > 0.8$).[23]

To identify the patterns of deformation and recovery of each cartilage thickness, we performed principal component (PC) analysis. First, the cartilage thickness values were normalized at the beginning of the running period (ie, 0 minutes) to show the thicknesses as a percentage change from the baseline values in both conditions over time. Then the normalized thicknesses during running at 7.5 and 8.5 km/h were stacked in 1 matrix together. Finally, PC analysis was used to extract the PCs and PC scores in the matrix. The PC scores between running at 7.5 and 8.5 km/h were compared using paired *t* tests. The PC scores that had >5% of variance accounted for (VAF) in the data were analyzed in the matrix. The statistical package SAS (version 9.4; SAS Institute Inc) was used for all tests.

Within- and between-sessions measurement consistencies of femoral cartilage thicknesses were calculated using the data at 0-minute measurements during each session. Specifically, 3 separate analyses of variance were performed for each thickness (2 for within-sessions and 1 for between-sessions) to obtain the between-subjects mean square (BMS) and the error mean square (EMS). The values were then entered into the following formula: ICC = (BMS − EMS)/BMS. To estimate the measurement precision, we calculated the SEM using the following formula: ($SEM = SD \times \sqrt{1 - ICC}$).[24,25]

RESULTS

Femoral Cartilage Thickness

We observed no condition by time interaction in intercondylar ($F_{20,656} = 0.76$, $P = .77$; Figure 3A), lateral condyle ($F_{20,649} = 0.56$, $P = .94$; Figure 3B), or medial condyle ($F_{20,655} = 0.84$, $P = .66$; Figure 3C) thickness. Regardless of time, all femoral cartilage thicknesses were consistently greater for the 8.5-km/h condition than the 7.5-km/h condition (intercondylar: $F_{1,656} = 24.73$, $P < .001$, $d = 0.15$; lateral condyle: $F_{1,649} = 16.60$, $P < .001$, $d = 0.16$; medial condyle: $F_{1,649} = 16.55$, $P < .0001$, $d = 0.12$). A time main effect was observed in intercondylar thickness ($F_{20,656} = 2.15$, $P = .003$), but a Dunnett-adjusted post hoc test revealed that none of the time points differed from the baseline value ($t_{677} < -2.02$, $P > .38$ for all comparisons). We observed no time main effects in lateral ($F_{20,649} = 0.76$, $P = .77$) or medial condyle ($F_{20,655} = 0.97$, $P = .49$) thickness.

The first 2 PCs explained >5% of VAF. We observed that PC1 and PC2 captured the variance of magnitude of cartilage thickness and time shift (eg, earlier versus later response of cartilage thickness) over time, respectively. Specifically, VAFs in the data of PC1 were 60%, 50%, and 67% for the intercondylar, lateral condyle, and medial condyle thicknesses, respectively. In addition, VAFs in the data of PC2 were 9%, 16%, and 8% for the intercondylar, lateral condyle, and medial condyle thicknesses, respectively. The results of paired t tests comparing PC scores between running speeds were not different for PC1 (intercondylar thickness: $t_{13} = -0.52$, $P = .61$; lateral condyle thickness: $t_{13} = 0.05$, $P = .96$; medial condyle thickness: $t_{13} = -1.52$, $P = .16$) or PC2 (intercondylar thickness: $t_{13} = 1.05$, $P = .32$; lateral condyle thickness: $t_{13} = -0.28$, $P = .78$; medial condyle thickness: $t_{13} = -0.64$, $P = .53$; Figure 4).

Step Count

A condition by time interaction was found in step count (condition × time: $F_{8,272} = 2.10$, $P = .04$; condition effect: $F_{8,272} = 53.41$, $P < .001$; Figure 3D). The 8.5-km/h condition showed more steps than the 7.5-km/h condition from 15 minutes (2434 versus 2359 steps; $t_{272} = -2.19$, $P = .03$, $d = 0.73$) until the end of running (6582 versus 6435 steps; $t_{272} = -4.26$, $P < .001$, $d = 0.57$).

Blood Lactate Concentration

We observed a condition by time interaction in BLC (condition × time: $F_{1,48} = 6.75$, $P = .01$; condition effect: $F_{1,48} = 4.42$, $P = .04$). Blood lactate concentration was increased after running at 7.5 km/h ($t_{48} = -2.90$, $P = .006$, $d = 1.34$) and 8.5 km/h ($t_{48} = -6.589$, $P < .001$, $d = 1.76$). Participants running at 8.5 km/h demonstrated higher BLC at postexercise ($t_{48} = -3.32$, $P = .002$, $d = 0.79$; Table 1).

Rate of Perceived Exertion

A condition by time interaction in the RPE was found (condition × time: $F_{1,48} = 11.66$, $P = .001$; condition effect: $F_{1,48} = 11.66$, $P = .001$). The RPE was increased after running at 7.5 km/h (12.7 versus 6.0; $t_{48} = -17.05$, $P < .001$, $d = 4.86$) and 8.5 km/h (14.5 versus 6.0; $t_{48} = -21.88$, $P < .001$, $d = 6.55$) compared with pre-exercise. Participants running at 8.5 km/h had a higher RPE postexercise (14.5 versus 12.7; $t_{48} = -4.83$, $P < .001$, $d = 1.00$; Table 1).

Reliability and SEM

Strong within-sessions (range, 0.91–0.96) and between-sessions (range, 0.83–0.91) reliability values were calculated. The average within- and between-sessions SEM were 0.09 and 0.15 mm, respectively (Table 2).

DISCUSSION

We examined how running intensity at different treadmill speeds affects acute deformation and recovery of femoral cartilage. As we expected, treadmill running at 8.5 km/h produced higher levels of physiological ($d = 0.79$) and psychological ($d = 1.00$) fatigue than treadmill running at 7.5 km/h. Contrary to our hypotheses, the deformation and recovery patterns of the femoral cartilage between running conditions over time did not differ. Although condition and time main effects were detected, the magnitudes of change were small ($d \leq 0.16$) between conditions, and no differences were observed in between-times post hoc comparisons. In other words, femoral cartilage thickness did not appear to change, whereas running at constant speeds of 7.5 and 8.5 km/h produced fatigue. Our study is the second investigation on the recovery of exercise-induced femoral cartilage deformation using ultrasonography. Our data are contrary to the results of the first study in which a linear recovery pattern regarding cartilage recovery was observed, but they are in line with the results from a recent systematic review, in which immediate changes in the femoral cartilage thickness after running were minimal.[3,26]

The condition effects with small effect sizes should be interpreted as an insignificant deformation in femoral cartilage between 7.5 and 8.5 km/h of treadmill running. This is contradictory to the previously suggested dose-dependent response where the magnitude of femoral cartilage deformation is related to exercise load.[3–5,14,27,28] Effects of running speed on joint kinematics and kinetics have been reported.[29,30] Along with differences in step counts in our study (Figure 3D), we think that our participants' running biomechanics while completing the 7.5- and 8.5-km/h running conditions were different. Therefore, the lack of differences in femoral cartilage deformation could be associated with things independent of running biomechanics. Although a decrease in cartilage stiffness is indicative of cartilage degeneration, the femoral trochlear is considered the stiffest cartilage in the knee joint.[31,32] In addition, femoral cartilage is known to have higher proteoglycan content than patellar cartilage.[33] These differences may, therefore, explain why we did not observe changes in femoral cartilage thickness, but many previous researchers studying tibial and patellar cartilage did.[11–13,15] Secondarily, our results could also be attributed to the range of assessment involved with measurement techniques. When the femoral cartilage is separately analyzed using magnetic resonance imaging scans, the medial portion has a larger deformation than the lateral portion.[5] However, our measurement technique is only able to capture part of the femoral cartilage (eg, anterior femoral trochlea). We acknowledge that our measurement technique is limited to comprehensively assessing femoral cartilage, which could have been associated with the lack of differences between running speeds.

The main outcomes in our study were obtained not only before and after but also in the middle of running, which required interruptions of running every 5 minutes. Our intention was to examine the interaction effect between intensity and duration of running on femoral cartilage deformation and recovery. In previous research (except for Pfeiffer et al), participants performed exercise continuously (without interruptions); thus, the cartilage deformation was examined pre-exercise and postexercise.[1,3–5,28] Therefore, a comparison of the magnitude (eg, percentage change) in femoral cartilage deformation between the exercise modes (interval versus continuous) would be meaningful; the results from the exercise mode with interval assessments (our study: <4% [not different]; previous study: <3% in walking) were relatively smaller than those from the continuous exercise mode (walking: <7%; drop landing: <10%; running: <9%).[1,3,4,28] As the previous data showed, our results could have been attributed to the exercise mode (eg, interval versus continuous).[4,28] In previous cartilage explant studies, researchers showed that the water content and the metabolism of chondrocytes are associated with the loading frequency.[34,35] Based on these data, we speculate that changes in the mechanical loading to the knee joint (eg, weightbearing to nonweightbearing due to running

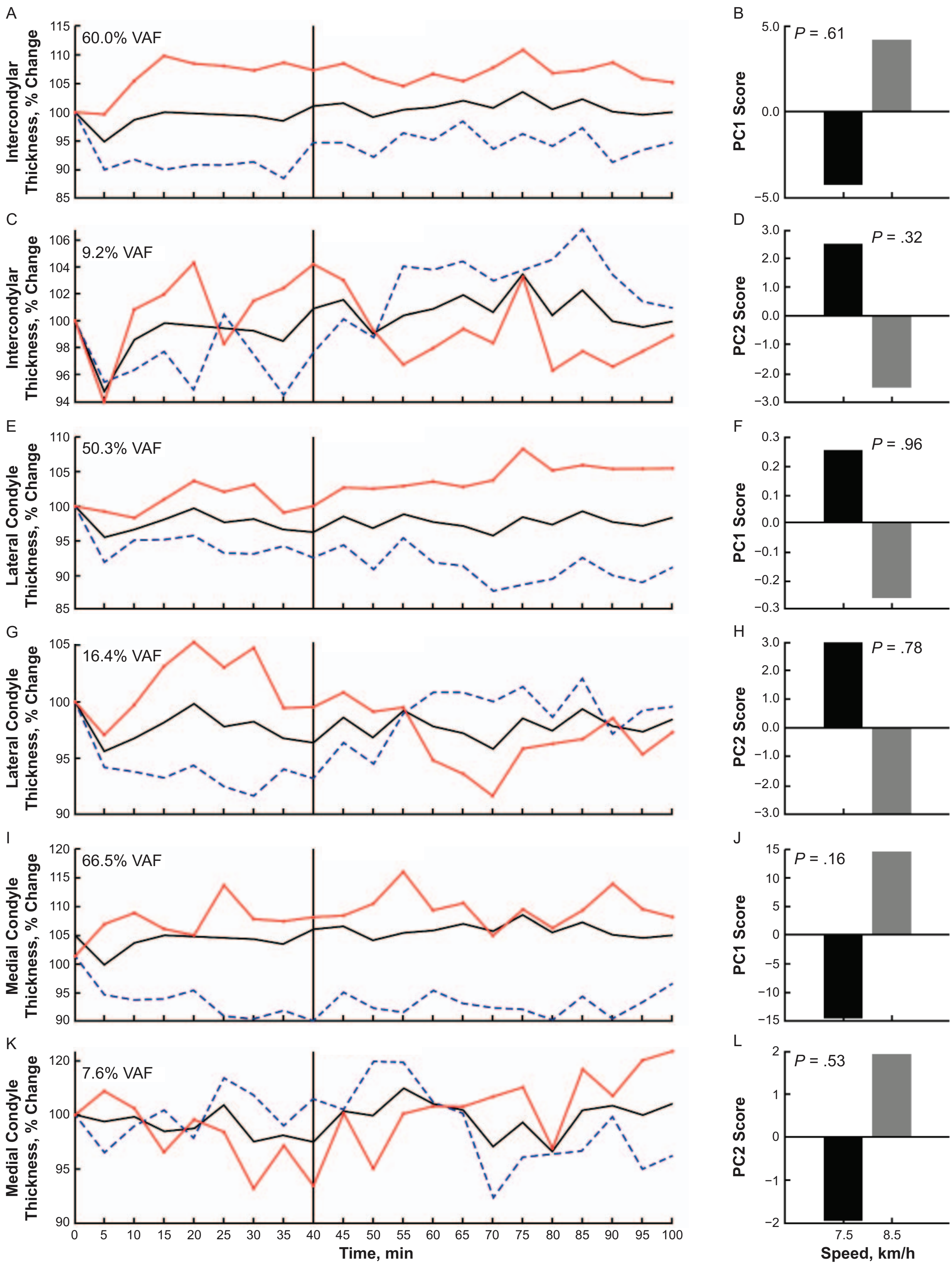

Figure 4. Variation in A–D, intercondylar; E–H, lateral condyle; and I–L, medial condyle thickness captured by the 2 principal components (PCs). A, C, E, G, I, and K: The black solid line depicts the mean thickness, and the blue and red lines show the effects of +1 SD (red line) and −1 SD (blue line) of PC scores on mean thickness. The vertical line distinguishes the treadmill running and recovery. B, D, F, H, J, and L: The mean of PC scores during 7.5 and 8.5 km/h. Abbreviation: VAF, variance accounted for.

Table 1. Blood Lactate Concentration and Rate of Perceived Exertion (Mean [95% CI])

Variable	7.5 km/h		8.5 km/h	
	Pre-exercise	Postexercise	Pre-exercise	Postexercise
Blood lactate concentration, mmol/L	1.5 (1.3, 1.7)	2.7 (2.1, 3.3)[a]	1.4 (1.2, 1.6)	4.1 (3.8, 5.1)[a,b]
Rating of perceived exertion[c]	6.0 (6.0, 6.0)	12.7 (11.8, 13.6)[a]	6.0 (6.0, 6.0)	14.5 (13.6, 15.4)[a,b]

[a] Different from pre-exercise ($P \leq .02$).
[b] Different from 7.5 km/h ($P < .01$).
[c] Borg scale for rating of perceived exertion.[21]

interruptions) could have assisted in the function of proteoglycans in maintaining hydration of the cartilage.[36] Activity-specific effects (eg, running) could also explain the result of no cartilage deformation in our data. Running consists of a short duration of the stance phase with a longer flight time such that the duration of mechanical load exertion to the knee joint is marginal. Fast cyclic loading during running could have resulted in an elevated stiffness in femoral cartilage, which could have limited exudation. Miller et al suggested that the duration of load application is counterbalanced by a higher impact (eg, >3 times compared with walking), which explains why distance runners are less likely to develop knee osteoarthritis.[36–38] Regarding fluid exchange, femoral cartilage deformation could be a result of the net effect on load-induced exudation and movement-induced reabsorption.[39] A balance between exudation and reabsorption from mechanical loading during treadmill running (including interval assessments) may have been insufficient to cause femoral cartilage deformation.

Our purpose—comparing the patterns of cartilage-thickness change every 5 minutes over time—yielded a study design with repetitive measures of ultrasonography (eg, 21 time points). Conducting an analysis of variance to examine the interaction between condition and time was necessary, and Dunnett correction was used to avoid the type I error rate in between-times comparisons (eg, post hoc tests on a time main effect); no difference means that cartilage thickness before running was maintained during the entire experiment (40 minutes of running and 60 minutes of recovery). Principal component analysis was performed to identify the key axes of variance in femoral cartilage data. Although 2 PCs were accounted for in our cartilage-thickness data, we observed no difference in the PC scores (Figure 4). This finding supports the results of parametric tests—femoral cartilage thickness did not change in response to running. In addition, the largest difference in cartilage thickness was 0.09 mm in our study, which is within the range of SEM values (Table 2). This finding also indicates that the observed differences would be trivial in real running.[25] The calculated SEM values were larger than those reported in previous studies (0.07 and 0.06 mm).[3,28] Although the measurement technique (our technician captured and analyzed >200 images for individuals' knees) and reliability (Table 2) were less likely to affect the results, the larger values relative to those of other studies could have been attributed to the number of participants (our study: n = 17; other studies: n = 25 and 43).[3,28]

Our study had several assumptions and limitations. First, 18 participants visited the laboratory at different times across the sessions. Given the characteristics of cumulative strain over the day, our results may have been confounded with typical diurnal changes in cartilage thickness.[40] Second, the degree of deformation as an acute cartilage response to exercise could be associated with the amount of water in the interstitial space at the knee joint; hydration status is one of the factors in the response of cartilage to mechanical load.[41,42] Therefore, one should assume that fluid circulation in and around the knee joint was similar across participants and between sessions. Lastly, variations in types of physical activity (eg, jogging, weightlifting, playing tennis, and playing soccer) in which our participants had been participating might also have affected the results. A longitudinal cohort study should be conducted to determine how different physical activities affect long-term cartilage adaptation.

CONCLUSIONS

Treadmill running at a constant speed of 7.5 or 8.5 km/h produced different levels of physiological and psychological fatigue. Although ultrasonographic assessments detected a change in the femoral cartilage thickness between running speeds over time points (every 5 minutes), the differences seemed to be negligible.

Table 2. Baseline Values

	Measurement	Mean ± SD, mm	Intraclass Correlation Coefficient	SEM, mm
Session 1[a]	Intercondylar thickness	2.15 ± 0.35	0.95	0.08
	Lateral condyle thickness	2.09 ± 0.34	0.91	0.10
	Medial condyle thickness	1.83 ± 0.44	0.96	0.09
Session 2[a]	Intercondylar thickness	2.16 ± 0.44	0.94	0.11
	Lateral condyle thickness	2.20 ± 0.48	0.95	0.10
	Medial condyle thickness	1.78 ± 0.40	0.96	0.08
Total[b]	Intercondylar thickness	2.20 ± 0.45	0.91	0.14
	Lateral condyle thickness	2.15 ± 0.35	0.89	0.12
	Medial condyle thickness	1.81 ± 0.44	0.83	0.18

[a] Within-between sessions reliability.
[b] Between-sessions reliability.

ACKNOWLEDGMENTS

This work was supported by the Ministry of Education of the Republic of Korea and the National Research Foundation of Korea (NRF-2021S1A5A2A01062062; Dr Jihong Park).

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