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Long Distance Running, Bone Density, Physiological Load Measures by Accelerometry and Joint Space Narrowing of the Knee

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Abstract

Objectives: Running is known to exert a positive impact on overall health. Its potential harm or benefit on knee osteoarthritis (OA) has, however, not been thoroughly explored, mainly due to lack of quantifiable metric to link running derived parameters with OA-related biomechanics. This study sought to investigate whether joint space width (JSW), an indicator of OA, is associated with a) acceleration magnitude at the knee level (associated with collision impact) and b) weekly running distance.

Design: This was a cross-sectional study using an open-label design.

Methods: We included 76 healthy volunteers (from sedentary individuals to trained runners). JSW was measured using standard fixed-flexion radiographs. A wearable 3-axial accelerometer was placed on the skin at the tibia plateau level to estimate acceleration magnitude during collision impact. An algorithm was designed to identify the exact instance of collision impact and measure its acceleration magnitude. Metaphysis density was assessed using tomodensitometry at the proximal tibia level (DENSISCAN). A multi-linear model was applied to assess whether running distance, collision acceleration, and metaphysis density were independent JSW predictors.

Results: Lower tibia collision acceleration was a predictor of JSW, whereas no association was found between JSW and running distance or metaphysis density.

Conclusions: Our results indicate that collision impact at the knee level (estimated by acceleration) may predict increased OA risk, while weekly running distance does not. While this collision impact may be related to running technique, further research is warrant to better understand the mechanism underlying high collision impact and its associated risks.

Keywords: Knee Osteoarthritis; Joint Space Width; Running Distance; Collision Acceleration; Wearable Technology

Introduction

It is well established that running is beneficial for our health and wellbeing, proven to reduce the likelihood of disability and early mortality when undertaken frequently. On the other hand, there are concerns that running may increase the risk of developing osteoarthritis (OA) [1]. OA is the most prevalent and costly form of arthritis and a major cause of morbidity in the elderly [2]. It is estimated to affect between 7% and 25% of Caucasians over 55 years old and expected to become the fourth most common medical condition in women [3].

Symptomatic knee OA, also known as idiopathic joint disease, is characterized by an imbalance between the synthesis and degradation of the joint cartilage and subchondral bone, accompanied by capsular fibrosis, osteophyte formation, and varying severities of inflammation of the synovial membrane. It occurs in approximately 6% of adults aged 30 and over, increasing in prevalence with age, reaching 10–13% in over 60 year-olds [4]. There are two subtypes: primary OA and secondary OA. Primary OA is generally related to aging and heredity, though its specific etiology is as yet undefined. Secondary OA is caused by disease, injury or lifestyle issues, such as obesity, joint trauma or repetitive joint use.

The OA prevalence, especially that affecting the lower limbs, is high in former elite athletes [5], probably due to their frequent use of excessive force potentially damaging the joints [6]. However, a putative link between knee loading and OA remains controversial [7].

Previous studies in healthy individuals suggest that running at slower speeds may either protect [8,9] or at least not exacerbate development of OA [1,10]. This strongly suggests that elite runners may avoid developing OA, though the issue has yet to be thoroughly investigated.

The cartilage's key function is to maintain the low-friction environment provided by the synovial fluid in combination with healthy articular cartilage. Cartilage thinning can increase the risk of joint diseases like OA [11]. Using radiography to measure the knee joint space, thus estimating cartilage thickness, is a common tool for assessing OA risk [8,12]. OA progression is believed to begin with joint cartilage thinning followed by the appearance of osteophytes and subchondral sclerosis. The latter is believed to result from increased burden in the bone area due to a diminished capacity of absorbing shock on account of cartilage thinning [10]. Clinically, the joint space width (JSW) of the knees, *i.e.,* the minimal distance between the two parts of the joint, can be measured using standard radiography. OA is strongly suspected when JSW thinning is observed, especially if accompanied by other symptoms, *i.e.,* pain, mobility limitations, osteophytes on radiography, and so on.

Taking all these observations together, OA risk appears to increase in athletes whose joints are subjected to high strain or shock during athletic activities [13,14]. Similarly, it could be hypothesized that knee JSW is related as much to the magnitude of the joint impact during running as to the frequency of impact.

This study sought to examine whether joint space width (JSW), an indicator of OA, is associated with acceleration magnitude at the knee level or weekly running distance.

To this end, we performed a cross-sectional study on runners and sedentary individuals in which we measured: a) JSW (fixed-flexion radiography of both knees), b) volumetric bone mineral

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density (BMD, high resolution tomodensitometry at the proximal tibia level), c) accelerations at the proximal tibia level. The latter variable was considered an indicator of the force (or strain) exerted at the bone level.

Though this population is, admittedly, not a population of elite athletes, it did represent individuals that often consult sport physicians complaining of knee pain.

Methods

Subjects

We recruited 76 male volunteers (age = 36 ± 7), 60 of whom were amateur distance runners having practiced for several years (at least five years). All were adults (age ≥ 18 years), healthy and free of any disorder like knee pain potentially influencing their activity or bone metabolism. Subjects with recent (< 2 years) joint/skeleton trauma were excluded. The protocol was approved by the local ethics committee. The subjects were categorized into three groups according to their running habits: 15 short-distance runners (Group 2: 5–30 km per week), 27 middle-distance runners (Group 3: 30–50 km per week), and 18 long-distance runners (Group 4: over 50 km/week). Weekly running distances were determined using daily running records. A group of 16 age-matched lean (BMI < 25), sedentary subjects (Group 1) were also recruited.

Maximal O_2 Uptake Measurement

Cardiorespiratory performance was quantified by VO_{2max} while running on a treadmill (Technogym, Runrace, Italy) through three-minute exercise bursts (increasing by 1.8 km/h from 7.2 km/h to exhaustion). The measurements were taken during the last 30 seconds of each burst using Quark b2 indirect calorimeter (Cosmed Ltd, Rome, Italy).

Submaximal Exercise Measurements

The subjects were instructed to run on a treadmill for five minutes at their self-selected preferred speed corresponding to their habitual running speed for long training sessions. They were asked to wear their habitual running shoes. Following acclimatization (*i.e.,* at least five minutes of running), accelerations at the proximal tibia during 570-second segments of recording were calculated using the 3-axial accelerometer, described below.

Acceleration Measurements

Lower limb accelerations during running were measured using an ambulatory data logger (Physilog®, Gait UP, CH). A small module comprising a 3D accelerometer (Analog Devices, ± 5 g) was attached to the external part of the right knee (close to the tibia plate). The signals were digitized (12 bit) at a sampling rate of 40 Hz and stored for off-line analysis on a static memory card (8 Mb).

A wavelet-based algorithm was developed to identify the exact moment of collision impact and estimate the vertical acceleration subjected to the tibia at the time of the impact. The details of the algorithm have been described in our previous publication [15]. In summary, the vertical acceleration signal (av) was first filtered (avf) based on the subject's speed (measured by treadmill) using an adaptive multi-resolution wavelet transform. This process provides an adaptive time-frequency resolution for extracting the signals beyond 0.31 Hz and under 5 Hz for lower speeds or 10 Hz for higher speeds. Then, acceleration peaks were identified by tracking changes in the acceleration difference extent between two consecutive samples. To reduce the artifacts, only acceleration peaks satisfying the thresholds set for inter-interval and magnitude were chosen for separation between two consecutive running steps. Initially, only peaks detected beyond a pre-defined threshold (from 0.1 g for lower speeds to 0.3 g for higher) were selected. Then, the median value of all remaining peaks was calculated and only those ≥ 80% of the median value were chosen for identifying running steps. For this, the peaks which satisfied a seed-adapted inter-interval threshold were selected. To estimate the exact time and magnitude of collision impact, the maximum peak of the non-filtered vertical acceleration (av) in an interval of three samples pre- or post-detected peak was identified. The average value of all detected acceleration peaks was then calculated to determine the average collision impact acceleration magnitude. All algorithms were developed using Matlab (The MathWorks-Matlab®). In addition, to automate the procedures and provide the final report as well as a graphical interface for verifying the accuracy of detection, a program based on LabVIEW (National Instrument-LabVIEW®) was developed.

Bone Mineral Density Measurement [15]

Appendicular tomodensitography (Densiscan®, scanco Medical, Bassersdorf/Zurich) was designed to measure the geometry and density of the long bones (radius, tibia). The accuracy of the method was estimated to be 0.3% as described by Deriaz O, et al [15]. For the measurements made at the proximal part of the tibia, the subject's leg was placed on a specially-built support of material transparent to the X-ray. The knee joint was carefully placed in the most proximal region of scanning. A scout view (*i.e.,* a digital X-ray in medio-lateral projection) was obtained on every scan for every millimeter in order to define the reference plane with a line tangent to the tibia plateau. The scans consisted of six tomograms at a distance of one millimeter from each to the tibia plateau (defined from the scout view by the reference line). The volumetric density of the subchondral bone was calculated from tomograms 3 to 6.

Knee Radiographs

A 30^0 standardized fixed-flexion protocol was used to obtain PA weight-bearing radiographs of both knees. The same experienced radiographer took all the radiographs using a fixed-film focus distance of 1.30 m. All knee radiographs were digitized using a film digitalizer at a 1.1-mm pixel resolution.

The minimum JSW of the medial and lateral tibiofemoral joint spaces were measured manually by two trained analysts in digitized radiographs. These analysts were blinded to the names and running categories of the participants. Reproducibility of these measurements, performed twice on a subsample of 20 subjects, was found to be excellent with an intraclass correlation coefficient of 0.98 for the mean JSW ($p < 0.001$).

Statistical Analysis

All of the continuous data were presented as mean ± standard deviation (SD). Analysis of variance (ANOVA) was used for between groups comparison for demographics as well as parameters of interest. Pairwise *Post Hoc* test was used to examine statistical significance difference between each two groups. Multiple linear regression was used to identify independent predictors for JSW (dependent variable). The independent variables used in the model were included running distance, tibia acceleration peak at the time of collision impact (an indicator of the collision impact magnitude), and volumetric BMD at the proximal tibia. The following confounding factors were introduced into the prediction equation: body weight, age, and squared age (to take into account the non-linearity of JSW with age as performed in some epidemiological studies [16]). The overall difference between groups was tested with an ANOVA. Tukey's HSD test was used for *post hoc* comparisons between groups. The Stata program (Version 13.0, Stata corp, College Station, TX) was used to perform the statistical analyses.

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Results

Table 1 summarizes the subject's demographics, respiratory performance, and metrics associated with JSW. No between group difference was observed in terms of age. However, noticeable between-group differences were observed for other demographic parameters, in particular between the long distance runners group (Group 4) and sedentary individuals (Group 1). In summary, body weight was, on average 13% (10 Kg) lower in the Group 4 than Group 1 ($p = 0.003$), while body height was on average 4% (7 cm) lower in the Group 4. As expected, long-distance runners exhibited significantly better cardiorespiratory performance compared to the sedentary subjects and on average had 34% higher VO_{2max} compared to short runners ($p < 0.001$).

No radiograph imaging revealed any degenerative joint disease (Table 1). Additionally, no noticeable between-group differences were observed for JSW values, suggesting walking distance had no impact on potential OA risk.

The subchondral volumetric BMD values at the proximal tibia are summarized in table 2. Long-distance runners habitually performing weekly walking distances of ≥ 30 km (Groups 3 and 4) exhibited higher subchondral volumetric BMD, by on average 13%, than the sedentary subjects ($p = 0.039$).

The self-selected comfortable speed was dependent on the running category: The highest-trained subjects selected, on average, 26% higher running speeds (2.5 km/h, $p < 0.001$) than the sedentary group (Table 3). Interestingly, despite the speed disparity, no between-group difference was observed for the magnitude of collision impact acceleration ($p = 0.898$), indicating that increases in magnitude of collision impact acceleration due to increases in running speed may be compensated by running training.

	Sedentary Runners (< 5 km/w) Group 1	Short-Distance Runner (5-30 km/w) Group 2	Middle-Distance Runner (30-50 km/w) Group 3	Long-Distance Runner (over 50 km/w) Group 4**	*P* - Value*
Number of subjects	16	15	27	18	
Body weight (kg)	77 ± 7[ab]	72 ± 8	71 ± 8[a]	67 ± 8[b]	0.003
Height (cm)	181 ± 5[a]b	178 ± 6	177 ± 7[a]	174 ± 6[b]	0.009
Age (years)	36 ± 6	36 ± 7	36 ± 7	36 ± 7	0.985
VO_{2max} ($mL.Kg^{-1}.min^{-1}$)	47 ± 4[abc]	58 ± 8[ad]	60 ± 6[b]	63 ± 8[cd]	< 0.001
Right knee med (mm)	5.4 ± 1.0	5.9 ± 1.2	5.9 ± 1.1	5.7 ± 0.8	0.372
Right knee lat (mm)	7.5 ± 1.3	7.2 ± 2.0	7.5 ± 1.1	7.3 ± 1.5	0.883
Left knee med (mm)	5.6 ± 1.1	5.6 ± 1.1	5.9 ± 1.1	5.7 ± 0.8	0.719
Left knee lat (mm)	7.2 ± 1.4	7.2 ± 2.0	7.3 ± 1.2	7.2 ± 1.3	0.986
Mean JSW med (mm)	5.5 ± 1.0	5.7 ± 1.0	5.9 ± 1.0	5.7 ± 0.6	0.544
Mean JSW lat (mm)	7.3 ± 1.2	7.2 ± 2.0	7.4 ± 1.1	7.3 ± 1.3	0.955
Mean JSW (mm)	6.4 ± 1.0	6.5 ± 1.1	6.7 ± 0.9	6.5 ± 0.9	0.821

Table 1: Subject demographic, respiratory performance, and joint space characteristics (Results with the same letter significantly differ Means ± SD, *overall differences between groups were tested using ANOVA, A Tukey HSD test was used for post hoc comparisons between groups. **from 51 to 97km per week; JSW: joint space width; means ± SD)

	Sedentary Runners (< 5 km/w) Group 1	Short-Distance Runner (5-30 km/w) Group 2	Middle-Distance Runner (30-50 km/w) Group 3	Long-Distance Runner (over 50 km/w) Group 4**	*P* - Value*
Proximal tibia metaphysis density ($mg.cm^{-3}$)	0.31 ± 0.04[ab]	0.33 ± 0.04	0.35 ± 0.06[a]	0.35 ± 0.04[ab]	0.039
Maximal acceleration (g) at most comfortable speed	2.8 ± 0.6	2.8 ± 0.9	2.7 ± 0.8	2.7 ± 0.9	0.893
Most comfortable running speed (km/h)	9.6 ± 1.3[abc]	11.7 ± 0.9[a]	11.3 ± 1.0[bd]	12.1 ± 0.8[cd]	< 0.001

Table 2: Volumetric subchondral BMD, accelerations values and running speed in function of the weekly running distance in the different groups of participants (Results with the same letter significantly differ Means ± SD; *overall differences between groups were tested using ANOVA, A Tukey HSD test was used for post hoc comparisons between groups; **from 51 to 97 km per week)

Variables	Coefficient	Standard error	T*	*P* - Value
Peak acceleration (g)	-0.29	0.13	-2.2	0.034
Running distance categories	0.06	0.11	0.55	0.587
Proximal tibia metaphysis density ($mg.cm^{-3}$)	1.4	2.3	0.61	0.544
Co-variables				
Age (y)	0.71	0.21	3.29	0.002
Squaredage (y^2)	0.010	0.003	-3.31	0.002
Body weight (kg)	0.006	0.013	0.47	0.640
Constant	-5.7	4.0	-1.45	0.151

Table 3: Results of a multiple linear regression for the prediction of the mean joint width at the tibia level (* t-test was used to assess whether the coefficient was different from zero. The overall multiple linear regression predicts significantly mean joint width ($F = 2.46$, $p = 0.03$))

Of the independent variables tested, only the magnitude of collision impact acceleration at the tibia level was a significant predictor of JSW, after adjustment for age and body weight (Table 3). In summary, irrespective of the running distance category or volumetric BMD at the metaphysis, those who exhibited higher collision impact acceleration at the tibia level had narrower JSW (p = 0.034).

Discussion

Implementing a cross-sectional design, we examined whether running conditions, *i.e.,* typical weekly distances and amplitudes of collision impact, can predict knee joint space narrowing in healthy knees. Our results suggest that irrespective of weekly running distances and bone mineral density, higher magnitude of collision impact acceleration at the tibia level is associated with narrower JSW after adjustment for age and body height. In other words, high impact shocks caused by collision impact during running are associated with narrow joint spaces in healthy knees. Given that joint cartilage thinning is one of the first predictors of the onset of OA [9,17], it can be postulated that individuals who subject their knees to high shocks may also be more at risk of developing this pathology. Our results are in accordance with the concept of stress on cartilage, which states that high-intensity heel strikes during running, associated with the biological and structural components that predispose OA, induce sufficient stress to be detrimental on the cartilage [18], whereas low-intensity heel strikes, for instance while walking may not be harmful [19]. This assertion is supported by a study which observed that repetitive mechanical stresses at high frequencies can modify the cartilage's 3D structure as observed on MRI performed with gadolinium immediately after a marathon race, in some joint areas, especially in the medialtibio-femoral compartment [20].

Moreover, results based on JSW and cartilage volume suggest that physical activity protects against OA [21], particularly regarding cartilage volume in children [22,23], while conversely, inactivity may favor OA [24]. However, the results of our study should be interpreted with caution, as JSW was measured on healthy knees, while it remains unclear whether high-amplitude shocks, associated with narrowing of "healthy" joints spaces, may effectively lead to OA. These results are apparently not in accordance with those of the Miller RH, et al [25] study on 14 subjects, in which their calculated "load per unit distance" (in order to explain why running may not predict OA) did not overshadow the importance of the peak joint shock in the pathogenesis of OA.

In our study, we chose to reproduce the subject's own training conditions, *i.e.,* with their shoes and at similar speeds to those of a habitual training session. Consequently, ours was not designed to determine whether the amplitude of the shocks may be due to running technique [26] or shoe type [27]. Nevertheless, we hypothesized that the difference in peak accelerations between runners could predominantly be explained by running technique, as runners probably change their shoes (type of shoe or state of shoes: new/used) more often than their technique.

Lastly, we did not observe any significant differences in JSW between the runners with different weekly running distances. These results are in accordance with the concept that running itself may not be an OA risk factor [9,11,25] though we can say it is associated with high strain on the joints. A study performed in the 1980's produced similar findings, observing that running pace was a better OA predictor at the hip level than running mileage [28]. On the other hand, the results from a recent animal study suggested that strenuous running predisposes subjects to OA [29], though this issue still requires more thorough investigation [1].

High-resolution tomodensitometry was also used to assess subchondral volumetric BMD. We observed an increase in the subchondral volumetric BMD of runners compared to those of the sedentary group (Table 2). This is compatible with the well-known beneficial effect of exercise on BMD, and has been discussed elsewhere [15]. Previous authors have also observed that subchondral BMD predicts joint narrowing in patients with OA [30]. In our cross-sectional study, we found no statistical relationship between subchondral BMD and JSW (Table 3). However, as mentioned above, our subjects were healthy runners with no signs of OA. It is therefore probable that a subchondral BMD-JSW relationship could be observed solely in patients with OA.

Conclusion

This study suggests that high vertical acceleration magnitude (shock) at tibia caused by collision impacts during running could narrow knee joint space irrespective of running speed and volume of exercise (*i.e.,* weekly running distance). It may also suggest that high amplitude of accelerations at tibia during running may be an indicator to evaluate potential harmful impact of running including increasing the risk of knee osteoarthritis. Additional prospective study is however warrant to confirm this finding.

Practical Implications

a. Weekly running distance does not appear to be related to osteoarthritis risk

b. Collision impact at the knee level may predict increased osteoarthritis risk

c. While collision impact may be linked to running technique, further research is warranted to better understand this issue

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Conflict of Interest

Authors declared that there is no conflict of interest.

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