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Research Article

Longitudinal change in femorotibial cartilage thickness and subchondral bone plate area in male and female adolescent vs. mature athletes

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SUMMARY

Little is known about changes in human cartilage thickness and subchondral bone plate area (tAB) during growth. The objective of this study was to explore longitudinal change in femorotibial cartilage thickness and tAB in adolescent athletes, and to compare these data with those of mature former athletes. Twenty young (baseline age 16.0 ± 0.6 years) and 20 mature (46.3 ± 4.7 years) volleyball athletes were studied (10 men and 10 women in each group). Magnetic resonance images were acquired at baseline and at year 2-follow-up, and longitudinal changes in cartilage thickness and tAB were determined quantitatively after segmentation. The yearly increase in total femorotibial cartilage thickness was 0.8% (95% confidence interval [CI]: −0.5; 2.1%) in young men and 1.4% (95% CI: 0.7; 2.2%) in young women; the gain in tAB was 0.4% (95% CI: −0.1; 0.8%) and 0.7% (95% CI: 0.2; 1.2%), respectively (no significant difference between sexes). The cartilage thickness increase was greatest in the medial femur, and was not significantly associated with the variability in tAB growth ($r = -0.19$). Mature athletes showed smaller gains in tAB, and lost >1% of femorotibial cartilage per annum, with the greatest loss observed in the lateral tibia. In conclusion, we find an increase in cartilage thickness (and some in tAB) in young athletes toward the end of adolescence. This increase appeared somewhat greater in women than men, but the differences between both sexes did not reach statistical significance. Mature (former) athletes displayed high rates of (lateral) femorotibial cartilage loss, potentially due to a high prevalence of knee injuries.

1. Introduction:

The growth of the human skeleton has been investigated in great detail over many developmental phases, mainly using X-ray technology. Because X-rays are not capable of delineating soft tissues and cartilage, the growth and maturation in these articular tissues has instead been described in animal models (Hayes et al., 2001; Hunziker et al., 2007; Khan et al., 2007; Meller et al., 2009), and little is known about how human articular cartilage grows and forms in diarthrodial joints. With the advent of novel magnetic resonance imaging (MRI) sequences that can depict articular cartilage directly (Eckstein et al., 2001, 2006b; Peterfy et al., 1994) and ultrasound, few studies have quantitatively assessed cartilage in children or adolescents (Jones et al., 2000; Spannow et al., 2010), and only one study has generated longitudinal data on cartilage growth (Jones et al., 2003). In this study, the patellar and tibial (medial and lateral) cartilage volume was measured in 74 male and female Australian children, aged 9–18 years, approximately 1.5 years apart (range 1.3–1.9). The authors (Jones et al., 2003) reported a significant increase in articular cartilage volume, peaking in Tanner stage two, which is approximately at age 10–13 (a stage that is defined by the breast buds forming and the areola beginning to widen in young women, and by a testicular volume of 1.6–6 ml, the skin on the scrotum thinning and enlarging, and with the penis length still unchanged in young men). Further, this peak change appeared to be greater in young men than young women (Jones et al., 2003). The authors further reported that articular cartilage volume growth in the tibia (but not in the patella) correlated significantly with change in body height, and that – in terms of cartilage volume gain – overweight children did not differ significantly from

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those with normal weight. Finally, tibial cartilage volume gain was greater in those who reported an average intensity of sport above the median (Jones et al., 2003).

However, a limitation of the above study was its focus on "cartilage volume" as a morphometric outcome. Cartilage volume is determined (a) by the (mean) thickness of the cartilage and (b) by the size of the subchondral bone plate area, i.e. the area of the proximal or distal bone extremity (epiphysis) that is physiologically covered by articular cartilage (Buck et al., 2010). Therefore, it remains unclear whether the observed gain in cartilage volume during adolescence (Jones et al., 2003), and the observed sex differences thereof, were due to an increase in (mean) cartilage thickness, or due to growth of bone and subchondral bone plate area (Buck et al., 2010). Although the authors (Jones et al., 2003) performed caliper measurements of thickness at distinct locations, they were concerned that these may not be representative of the entire joint. Finally, the correlation seen between gain in cartilage volume and body height (Jones et al., 2003) may also be mediated by bone growth. The objective of the current study was therefore to answer the following questions:

(a) Does the longitudinal change of knee cartilage thickness (and subchondral bone plate area) in adolescent athletes differ from that in mature athletes, who experienced a similar loading history (Carter and Wong, 1988) earlier in their lives and are still physically active?
(b) Are there differences in longitudinal growth rates between male and female study participants?
(c) Is there an (individual) association of cartilage thickness change with the growth of the subchondral bone plate areas?

Such data are not only of theoretical interest: recently, great attention has been paid to measuring cartilage volume and thickness change after trauma, for instance after rupture of the anterior cruciate ligament (ACL) (Frobell et al., 2009; Frobell, 2011). Such measurements are useful, for instance, in evaluating the structural efficacy of surgical treatment (i.e. ACL repair) or other interventions, in an attempt to combat incident posttraumatic osteoarthritis (OA). ACL ruptures often occur in young athletes, and in the above studies (Frobell et al., 2009; Frobell, 2011) a longitudinal gain in cartilage volume and thickness was observed post-injury and was interpreted as a potential sign of (pathological) cartilage swelling. Therefore, longitudinal reference data in healthy adolescent athletes are needed, to be able to evaluate longitudinal changes in cartilage post-injury.

2. Material and methods

2.1. Study population

We studied 40 top volleyball athletes: the adolescent group was at this time active at the Olympiastützpunkt (OSP) Berlin; they were aged 16.0 ± 0.6 years at baseline (10 male; 10 female) and trained twice per day for approximately 2 h (Table 1). Training was focused on strength, endurance, individual volleyball skills, and team playmaking strategies. Of the 10 boys, 2 had Osgood Schlatter disease, 1 had back pain, 2 had back pain as well as jumper's knee, 1 had scoliosis, 1 had kidney issues, and 1 had had a medial meniscectomy in the knee contralateral to the one examined. Of the 10 girls, 1 had an ACL tear in the knee studied, 1 had an ACL and meniscus tear in the contralateral knee, 2 had knee pain (1 in combination with back pain), 1 had back pain and jumper's knee 1 in combination with issues with the Achilles tendon, 2 had muscle pain, 1 had shoulder pain, and 1 had pain in both tibiae. The mature group consisted of former elite athletes, also from the OSP, who were on

Table 1
Demographic data of the study participants.

	Adolescent		Mature	
	Girls	Boys	Women	Men
No	10	10	10	10
Age	15.7 ± 0.5	16.3 ± 0.6	46.6 ± 6	46.1 ± 3
Height	182 ± 4	194 ± 5	176 ± 5	191 ± 5
Weight	70 ± 9	84 ± 5	71 ± 6	95 ± 13
BMI	20.9 ± 2	22.3 ± 0.9	22.7 ± 1.9	26.6 ± 2
# With knee pain (CL)	2 (2)	2 (2)	2 (2)	4 (2)
# ACL/Mx	1 (1)	0 (1)	3 (1)	3 (2)

ACL/Mx, ACL or meniscus surgery [usually meniscectomy] in the same knee (in the contralateral knee [CL]).

average 30 years older than the adolescent participants (46.3 ± 4.7 years; 10 men, 10 women, Table 1). All mature athletes were still currently playing volleyball at least twice a week. Of the 10 men, 3 had back pain (1 with a previous disk prolapse), 3 had back and knee pain (1 with lateral meniscectomy and 1 with other previous knee surgery), and 2 others had had meniscus surgery previously. Of the 10 women, 1 had a jumper's knee and a previous Achilles tendon rupture, 3 had hip arthritis (1 with endoprosthetic surgery), 2 had knee pain (1 combined with back pain), 2 had had meniscus and 1 had had other surgery in the imaged knee, and 1 had had meniscus surgery in the contralateral knee. The study protocol was approved by the local ethics committee and all participants (and/or their parents) had signed informed consent to participate in the study.

2.2. Image acquisition using MRI

Baseline and 2-year follow-up MR images of the dominant knee (the leg used for take-off) were acquired using a 1.5 T MRI scanner (Avanto, Siemens Medical Systems, Erlangen, Germany) and a dedicated 8-channel knee coil. To minimize the potential impact of the "daytime" on cartilage thickness (Sitoci et al., 2012), the images were always acquired in the morning (i.e. between 8 a.m. and 12 noon). All patients were positioned with the knee joint in the center of the coil, and with the leg almost in extension. A comprehensive set of MRI pulse sequences was acquired, with the sagittal 3D VIBE sequence with water excitation (1.5 mm slice thickness; 0.31 mm in-plane resolution, repetition time = 14.6 ms, echo time = 6.5 ms, flip angle = 20°) used for cartilage quantification (Figs. 1 and 2). The follow-up acquisitions were made approx. 2 years after baseline imaging (24.3 ± 0.9 months; range 21–27), with all acquisition parameters being kept identical (Fig. 1). One adolescent girl had to be excluded due to limited image quality of the baseline data set, and one adolescent boy was excluded due to missing follow-up data.

2.3. Image segmentation and analysis

The two knee image data sets per participant were processed with blinding to the time point of the acquisition (i.e. baseline and follow-up); a random time point was processed first, the other time point was processed second, using the first data set as a reference.

The subchondral bone plate area (i.e. the interface between the cartilage and the subchondral bone) and the cartilage surface were segmented manually in each image showing the medial (MT) and lateral tibia (LT), and the weight-bearing (central) part of the medial (cMF) and/or the lateral femoral condyle (cLF) (Fig. 2). The weight-bearing aspect of the femoral condyles was separated from the posterior aspects using a 75% distance measure between the inter-condylar notch and the most posterior aspect of the condyles (Eckstein et al., 2009).