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Load-specific differences in the structure of femoral neck and tibia between world-class moguls skiers and slalom skiers

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Bone structure of weight-bearing proximal femur and tibia was examined among the Finnish world-class moguls skiers and slalom skiers. We hypothesized that these bones, during typical sport-specific performance, had been subjected not only to extreme loading but also to distinct loading in terms of rate and primary direction. Bone [dual-energy X-ray absorptiometry (DXA), peripheral quantitative computed tomography (pQCT), magnetic resonance imaging] and muscle performance data of the lower extremities were obtained from the five Finnish male moguls skiers and six slalom skiers competing at the World Cup level. Data (DXA, pQCT) from 12 age- and weight-matched normally active men were used for comparison. The ANCOVA with body height as a covariate was used for statistical analysis. The weight-bearing bones of the athletes were 10–60% stronger than those of the normally active men. Compared with the moguls skiers, the slalom skiers showed an average 43% thicker anterior cortex at the narrowest region of the femoral neck. This study suggests that the bone structure at skiers' heavily loaded lower extremities was very robust. A specific finding was the thick anterior cortex of the femoral neck among the slalom skiers. Apparently, the predominant loading type had modulated the site-specific skeletal response to physical exertion.

Strong, well-coordinated muscle activity is vital for efficient and safe movements under extreme loading, while robust bone structures most likely emerge as a consequence of this kind of activity. Extreme sports offer natural experiments that could never be carried out in controlled settings but, as Ruff has stated, they demonstrate the potential for bone to adapt when the loading circumstances change (Ruff, 2006). Obviously, the information obtained from athlete studies is not directly transferable to clinical prevention of bone fragility, but it may facilitate the search for an optimal osteogenic stimulus based on physical exercise.

It was recently shown that the cortical thickness at the femoral neck, particularly the thin inferoanterior–superoposterior axis, can predispose the femoral neck to fragility fractures during a sideways fall (Lotz et al., 1995; Bell et al., 1999a, b; Mayhew et al., 2005). Given the established ability of bone to adapt its structure to the prevalent loading environment (Frost, 2003; Ruff et al., 2006), one mechanism leading to this direction-specific cortical deterioration might pertain to locally reduced stresses within the given cortical site (Crabtree et al., 2001). Based on extensive series of studies (Bell et al., 1999a, b; Mayhew et al., 2005), Mayhew and colleagues suggested that the preservation of cortical stability at the femoral neck might require regular lifelong mechanical loading that is targeted specifically to the thin cortical regions, and comprise exercises particularly involving hip straightening and extension movements from a flexed position, such as sculling, gymnastics, and weights.

The functional adaptation of bone to physical exercise is related to the number, magnitude, rate, and distribution of load-induced stresses within the bone (Ruff et al., 2006). Apparently, a long-lasting and monotonous performance producing a large number of similar, relatively small loads (e.g., endurance running) is not as osteogenic as a physical performance involving relatively few high-magnitude and high-rate load cycles and sufficient variation in the loading milieu. Triple jump provides an impressive demonstration of osteogenic impact loading to the maximum, the instant ground reaction forces reaching up to 20 times the body weight onto a single leg, while the structural strength of loaded bones is some 30% greater compared with normally active referents (Heinonen et al., 2001).

From a clinical perspective and the safety aspect, exercises involving extreme jumping can be unfeasible to be used as a general health strategy to prevent bone fragility. In contrast, odd-impact exercises (Nikander et al., 2005, 2006) exerting adequate loading to the lower extremity skeleton from unusual lateral directions, but without very high vertical impacts, may offer a comparably osteogenic option to enhance bone rigidity and strength without exposing the cartilage tissues and joints to an increased risk of injury. Although shown to be somewhat beneficial to the femoral neck rigidity, the common physical activities, such as cycling and weightlifting including the abovementioned hip straightening and extension movements, cannot rival with the odd-impact racket games, step aerobics, speed skating, or soccer in terms of apparent osteogenicity (Nikander et al., 2005). However, convincing evidence on the true effects of specific physical loading on the clinically important cortical structure of the femoral neck is virtually lacking mainly because of methodological limitations in the commonly used dual-energy X-ray absorptiometry (DXA) method (Sievänen, 2000; Bolotin et al., 2001).

In this study, we investigated the true cross-sectional bone structure at the weight-bearing lower extremities, including a unique magnetic resonance imaging (MRI) assessment of the femoral neck, among freestyle skiers (moguls) and alpine skiers (slalom). In these two athlete groups, the bones of the lower extremities had apparently been subjected to not only very heavy loading but also very distinct loading patterns in terms of rate and direction.

Material and methods

Subjects

Bone and physical performance data could be obtained from five male moguls skiers and six slalom skiers of the Finnish team competing at the World Cup level. The study protocol was approved by the Ethics Committee of The Pirkanmaa Hospital District, and each participant gave his written informed consent before the measurements. For the general comparison of these athletes' bone characteristics with non-athletic referents, data from 12 age- and weight-matched normally active men were obtained from our previous study (Torvinen et al., 2003).

Description of the sport performances

A typical moguls performance includes straightforward downhill skiing along a steep (up to 32°) and a very bumpy slope as quickly as possible, including two landings from aerial maneuvers. A typical slalom performance, in turn, includes zigzag-type, rapidly alternating changes in the skiing direction along a slope with varying steepness, virtually without high vertical impacts (Berg et al., 1995; Bauer & Zerpa, 1996). The flexed skiing position with bent hip and knees, common to both of these sports, requires a high capability of muscles to produce rapid eccentric forces for compensation of high vertical (moguls) or centrifugal (slalom) ground reaction forces. Associated joint moments, taking the incident dynamic muscle forces and lever arms of the body into account, are significant determinants of mechanically competent bone structures (Lovejoy, 1988; Biewener, 1989; van der Meulen & Carter, 1995; Moisio et al., 2004; Nikander et al., 2006).

Training history

Information on sport-specific training hours per week during the previous year, sport-specific training years, start of the competing career, and the proportion of cross training such as weightlifting, sustained sports injuries, and medical history were collected via a recalled training questionnaire.

Muscle performance

The maximal isometric leg extension force was measured with a leg press dynamometer (Tamtron, Tampere, Finland). In our laboratory, the precision (coefficient of variation, %) of this measurement is about 5% (Heinonen et al., 1994). For the athletes only, the dynamic maximal take-off and landing forces and power were measured with a force-plate (Kistler Ergojump 1.04, Kistler Instrumente AG, Winterthur, Switzerland) during squat and counter-movement jumps. The precision of the vertical jump measurements is 2.6% (Torvinen et al., 2002).

Bone characteristics

Dual-energy X-ray absorptiometry (XR-26 Norland Inc., Fort Atkinson, Wisconsin, USA) was used to provide a common clinical measure, areal bone mineral density (aBMD) of the femoral neck and lumbar spine (L2–L4). The *in vivo* precision of the aBMD measurements is better than 1% in our laboratory (Sievänen et al., 1996).

The DXA-based comparison of the femoral neck structure between the athletes and referents was carried out with hip strength analysis (HSA) (Beck et al., 2000). The cross-sectional area occupied by bone mineral (CSA, mm^2), subperiosteal width (W, mm), and section modulus (Z, mm^3), an index of bone strength against bending, were determined at the narrowest neck section. In our laboratory, the *in vivo* precision [coefficient of variation (CV%)] is 2.7% for CSA, 2.5% for W, and 4.8% for Z (Nikander et al., 2005).

Peripheral quantitative computed tomography (pQCT, XCT3000, Stratec Medizintechnik GmbH, Pforzheim, Germany) was used to measure the distal tibia (5% proximal to the distal endplate of the tibia) and the tibial midshaft (50% proximal to the distal endplate of the tibia) according to our standardized scanning and analysis procedures (Sievänen et al., 1998). For the distal site, bone mineral content (BMC, g), total cross-sectional area (ToA, mm^2), mean cortical cross-sectional wall thickness (CWT, mm), trabecular density (TrD, mg/cm^3), and density-weighted polar section modulus [an index of bone strength against torsion (BSI), mm^3] were determined. For the cortical midshaft, besides the BMC, ToA, and CWT, cortical density (CoD, mg/cm^3) was determined. In our laboratory, the *in vivo* CV% varied from 0.9% (TrD) to 4.2% (BSI) at the distal tibia, and from 0.7% (CoD) to 2.5% (BSI) at the tibial shaft (Sievänen et al., 1998).

Finally, MRI (Gyroscan 1.5T Intera Power, Philips Medical Systems, Best, The Netherlands) was used to measure the athletes' actual cortical structure at the narrowest femoral neck cross-section according to our recent standard procedure (Sievanen et al., in press). Based on precise (CV% about 1%)

assessments of the periosteal and endosteal circumference of the cortical wall, the ToA was determined, and the torsional rigidity (Z) of the thin-walled cross-section of the femoral neck was estimated using the classic Bredt's formula (Sievanen et al., in press). In addition, direction-specific mean cortical wall thickness (CWT) at anterior, posterior, superior, and inferior quadrants of the cortical bone was separately assessed (Fig. 1).

Statistics

Statistical analyses were performed with SPSS (Version 11.0; SPSS Inc., Chicago, Illinois, USA). Means and standard deviations (SD) are given as descriptive statistics. One-way analysis of variance (ANOVA) was used for evaluating subject characteristics and between-group differences in muscle performance, training history, and the ratio between the superior to inferior wall thickness of the femoral neck. Differences between the athlete groups in bone variables other than the dimensionless ratios were estimated by analysis of covariance (ANCOVA) using body height as the covariate. A P-value <0.05 was considered to be statistically significant.

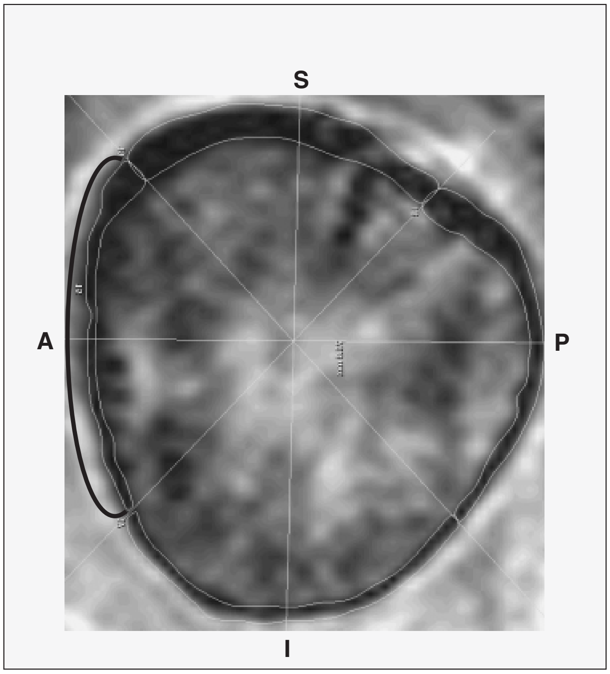

Fig. 1. Magnetic resonance image of the femoral neck cross-section at its narrowest location. Periosteal and endosteal cortical boundaries and the cortical quadrants are indicated.

Results

Subject characteristics and muscle performance data are shown in Table 1. Slalom skiers were shorter than moguls skiers and referents in general. Training history was quite similar between the athlete groups. The sports-specific training years averaged about 15 years, and the mean weekly training hours exceeded 15 h. The weight training in both athlete groups comprised similar weight training movements such as squats and leg press with heavy weights, up to the personal maximum, and the proportion of weight training was about 25% of the total training hours in both groups. Muscle performance was quite identical between the moguls skiers and slalom skiers, and as expected, the athletes' isometric leg extension force was on average 20–30% higher compared with that of the referents ($P<0.05$).

Of note, six out of 11 athletes reported to have suffered from a major sport injury, such as anterior cruciate ligament injury or lower extremity fracture, during their career, but not within the preceding year before the study measurements.

Bone characteristics

The lumbar spine and femoral neck aBMD, HSA results at the femoral neck and pQCT results at the distal tibia and tibial midshaft, and respective height-adjusted comparisons between the athletes and referents are shown in Table 2. The aBMD values were on average 13% (moguls skiers' lumbar spine) to 19% (slalom skiers' femoral neck) higher compared with the referents. Likewise, the tibial BMC was 18% (slalom skiers' tibial shaft) to 39% (slalom skiers' distal tibia) higher compared with the referents.

At the tibial midshaft, the athletes' bone was somewhat larger (10–15%) and thicker (13–15%)

Table 1. Subject, training, and muscle force characteristics of the skier groups and reference group (mean, SD)

	Mean (SD)		
	Moguls skiers ($N=5$)	Slalom skiers ($N=6$)	Referents ($N=12$)
Age (years)	22.6 (4.5)	24.5 (2.9)	24.3 (3.6)
Height (cm)*	181.9 (7.2)	173.5 (3.7)	180.6 (3.7)
Weight (kg)	77.2 (8.4)	76.6 (4.3)	76.2 (7.9)
Isometric leg extensor force (kg)*	320 (40)	351 (34)	267 (45)
Counter movement jump, take-off force (N)	2051 (116)	2158 (116)	–
Counter movement jump, take-off force/body weight (N/kg)	26.8 (1.4)	28.3 (2.6)	–
Power in counter movement jump/body weight (W/kg)	60.8 (3.5)	59.9 (5.7)	–

*Note the statistically different values ($P<0.05$) between groups in body height and isometric leg extensor force.

Table 2. Absolute pQCT and DXA values (mean, SD) in moguls skiers, slalom skiers, and referents, and the body height-adjusted percentage differences compared with the referents

	Moguls skiers Mean (SD)	% difference compared with the referents % (95% CI)	Slalom skiers Mean (SD)	% difference compared with the referents % (95% CI)	Referents Mean (SD)
Lumbar spine (DXA)					
aBMD (g/cm^2)	1.258 (0.102)	13 (2–25)*	1.221 (0.182)	16 (3–29)*	1.104 (0.075)
Femoral neck (DXA)					
aBMD (g/cm^2)	1.157 (0.059)	15 (6–26)*	1.151 (0.097)	19 (7–31)*	1.000 (0.084)
Bone cross-sectional area (mm^2)	421 (35)	20 (10–30)*	420 (38)	24 (13–35)*	350 (20)
Periosteal width (mm)	35.9 (2.8)	5 (−4 to 13)	35.7 (2.1)	7 (−2 to 18)	34.2 (2.6)
Section modulus (mm^3)	2415 (359)	25 (10–41)*	2443 (238)	34 (16–54)*	1914 (187)
Tibial shaft (pQCT)					
BMC (mg)	1200 (117)	24 (10–41)*	1128 (135)	18 (3–36)*	964 (101)
Total area (mm^2)	632 (85)	15 (4–26)*	584 (31)	10 (−2 to 22)	546 (37)
Mean cortical wall thickness (mm)	6.2 (0.3)	15 (1–30)*	6.0 (0.6)	13 (−2 to 30)	5.4 (0.7)
Cortical density (mg/cm^3)	1111 (38)	3 (−1 to 7)	1123 (25)	2 (−2 to 6)	1082 (38)
Polar section modulus (mm^3)	3007 (441)	30 (13–49)*	2594 (330)	13 (−3 to 32)	2303 (217)
Distal tibia (pQCT)					
BMC (mg)	1076 (120)	25 (13–39)*	1099 (105)	39 (23–56)*	850 (87)
Total area (mm^2)	1124 (152)	11 (−3 to 27)	1077 (62)	13 (−3 to 31)	1004 (131)
Cortical wall thickness (mm)	3.1 (0.6)	63 (24–114)*	3.3 (0.8)	82 (34–149)*	1.9 (0.5)
Trabecular density (mg/cm^3)	275 (6)	11 (2–20)*	290 (25)	20 (9–32)*	248 (19)
Polar section modulus (mm^3)	2369 (292)	42 (13–80)*	2481 (453)	61 (24–109)*	1664 (374)

*Note that when the zero is not within the given 95% confidence interval (95% CI), the result is statistically significant ($P < 0.05$).

DXA, dual-energy X-ray absorptiometry; pQCT, peripheral quantitative computed tomography; BMC, bone mineral content; aBMD, areal bone mineral density.

than that of the referents, but CoD showed no group differences (Table 2.).

At the distal tibia, the athletes' bone gain in BMC was attributable to a somewhat larger (11–13%) ToA and especially to strikingly thicker (63–82%) bone cortices. The TrD was also somewhat higher among the athletes (11–20%) than referents.

As a consequence of the above-noted structural modifications, the mechanical rigidity of the distal and midshaft sections of the athletes' tibiae was substantially higher than that in the referents', the tibial rigidity being 30% higher at the moguls skiers' midshaft and even 61% higher at the slalom skiers' distal site (Table 2).

Figure 2 shows the height-adjusted percentage differences in the pQCT variables measured at the distal tibia and tibial midshaft between the moguls skiers and slalom skiers. Although none of the differences reached statistical significance, the borderline between-group differences in the TrD of the distal tibia (~8%), favoring the slalom skiers, and that in the polar section modulus of the tibial midshaft (~15%), favoring the moguls skiers, are worth noting. Figure 3 illustrates the difference in the tibial midshaft geometry between the athlete groups; the antero-posterior diameter was elongated and the relative thickness of the anterior cortical wall was higher among the moguls skiers ($P < 0.05$).

Table 3 shows the height-adjusted MRI data of the femoral neck and a comparison between the athlete groups. While the ToA was similar among the athletes, the torsional rigidity of the femoral neck appeared to be about 10% higher among the slalom skiers, but did not reach statistical significance. Noteworthy, the slalom skiers' anterior cortical wall was significantly (43%, $P < 0.05$) thicker than that in the moguls skiers. Similarly, non-significant trends, in favor of the slalom skiers, were observed at

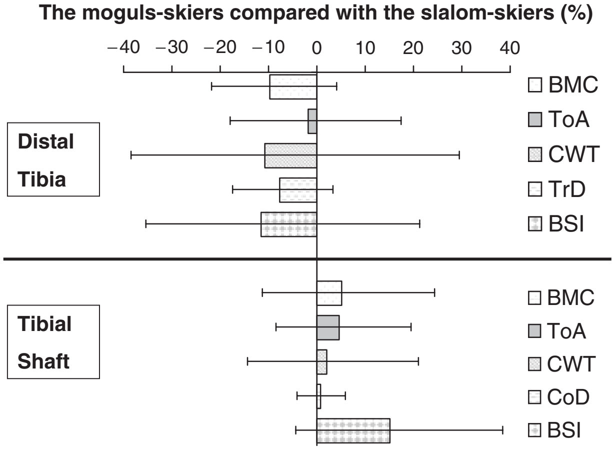

Fig. 2. Body height-adjusted mean percentage differences (95% CI) between the moguls skiers and slalom skiers in peripheral quantitative computed tomography-measured bone mineral content (BMC), total cross-sectional area (ToA), mean cortical cross-sectional wall thickness (CWT), trabecular density (TrD), cortical density (CoD), and bone strength index (BSI) at the distal tibia and tibial midshaft. The slalom skiers' mean value denotes the reference line.

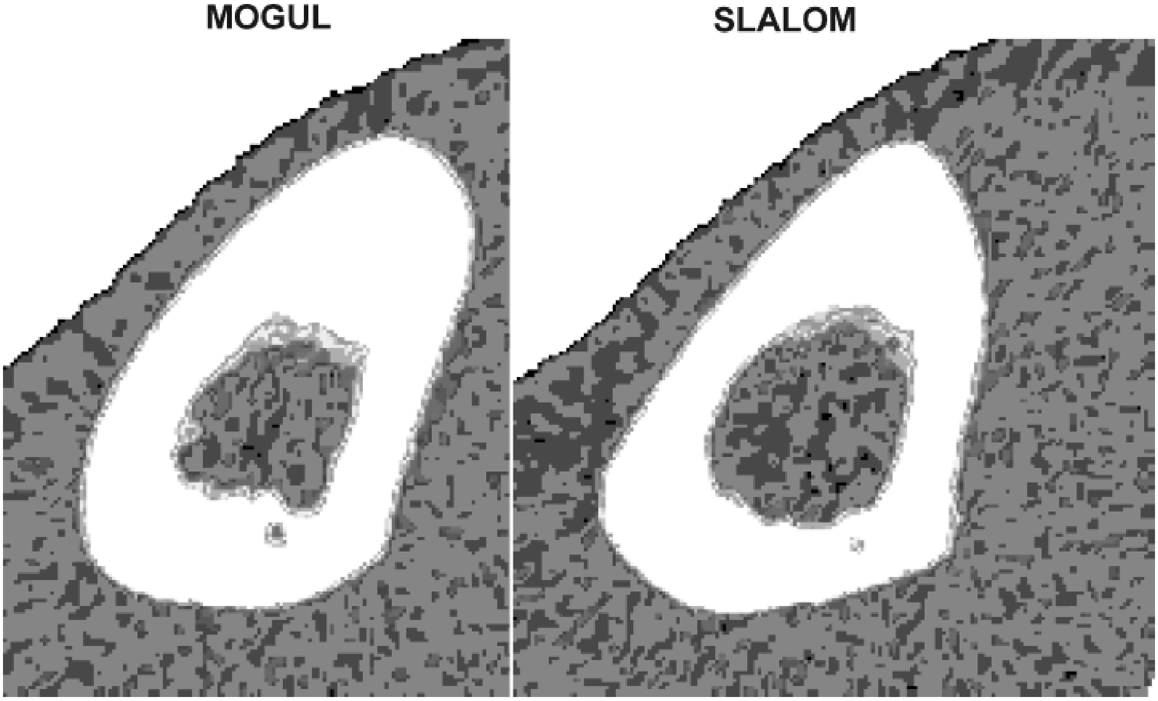

Fig. 3. Peripheral quantitative computed tomography images of the tibial midshaft scanned from a moguls skier (left image) and a slalom skier (right image). Note the distinct difference in the shape of the bone cross-section. The antero-posterior diameter was elongated and the relative thickness of the anterior cortical wall was higher among the moguls skiers ($P < 0.05$).

Table 3. Body height-adjusted femoral neck MRI data in moguls skiers and slalom skiers and the percentage differences between the groups

	Mean (SD)		% difference between the moguls and the slalom skiers, % (95% CI)
	Moguls skiing	Slalom skiing	
Femoral neck (MRI)			
Total area (mm^2)	905 (53)	881 (47)	2.6 (– 16.2–25.6)
Section modulus (mm^3)	2462 (169)	2234 (151)	9.8 (– 14.2–40.6)
Segmental analysis (quadrants)			
Anterior cortical wall thickness (mm)	0.7 (0.1)	1.1 (0.1)	– 42.6 (– 60.8– – 15.9)*
Posterior cortical wall thickness (mm)	0.8 (0.1)	1.0 (0.1)	– 25.6 (– 49.2–8.8)
Superior cortical wall thickness (mm)	1.0 (0.2)	1.5 (0.2)	– 38.9 (– 68.0–16.7)
Inferior cortical wall thickness (mm)	0.8 (0.1)	0.8 (0.1)	1.7 (– 34.8–58.7)

*Note that when the zero is not within the given 95% confidence interval (95% CI), the result is statistically significant ($P < 0.05$).

MRI, magnetic resonance imaging.

the superior (39%) and posterior (26%) quadrants of the femoral neck, but not at the inferior quadrant.

Discussion

The bone results in this study were in line with the conclusions of previous athlete studies (Haapasalo et al., 2000; Rittweger et al., 2000; Heinonen et al., 2001, 2002; Kontulainen et al., 2002; Faulkner et al., 2003; Liu et al., 2003; Nikander et al., 2005, 2006) that the heavily loaded bone structures among top-level athletes can be very strong, in this study, even up to 60% stronger (the distal tibia of the slalom skiers) compared with normally active men. In general, the strong bone structure was characterized by a very thick cortex, a high TrD close to the apparent ceiling value (Heinonen et al., 2001), and a somewhat larger bone cross-sectional size. A particularly noteworthy and novel finding of this study was that some structures of the bones (geometry of tibial diaphysis and anterior cortical thickness of femoral neck) were distinct between the two studied extreme athlete groups. Apparently, this finding reflects the strong influence of predominant sport-specific loading (e.g., magnitude, rate, direction) on skeletal response to physical exertion.

The typical bone-loading milieu among the moguls skiing and slalom skiing can be distinguished as follows: while the flexed skiing position with bent hip and knees in conjunction with the absolute requirement for high-power muscle performance is common to both of these sports, the moguls skiers primarily need to do substantial eccentric muscle work to cope with the successive vertical ground reaction forces caused by rapid, straightforward skiing down the steep and bouncy hill. They also keep their lower limbs parallel (side by side) in the natural position, and their lower extremities have to cope with the hard landings from high aerial maneuvers while maintaining the skiing speed. The slalom skiers, in turn, need to do a lot of eccentric muscle work to counteract the centrifugal ground reaction forces caused by successive turns to varying directions performed at a high speed.

Although we were not able to measure the loading characteristics directly during the skiing performances, we obtained carefully measured, detailed information of loading of these sports from the national Research Institute for Olympic Sports (unpublished data, The Research Institute for Olympic Sports, Jyväskylä, Finland, 2005). Of note, some of our skiers were assessed in both of these studies. Regarding the moguls skiing, the highest ground reaction forces during the downhill skiing phase are, surprisingly, only two times the body weight, which is similar to loads caused by brisk walking (Vainionpaa et al., 2006). These low reaction forces most likely reflect the function of the moguls skiers' hip muscles as active shock-absorbers during the skiing performance. In contrast, the ground reaction forces during a slalom skiing performance can be four to five times the body weight (Yee & Mote 1997; unpublished data, the Research Institute for Olympic Sports, Jyväskylä, Finland, 2005), corresponding to typical reaction forces during running (Vainionpaa et al., 2006) and jumping (Heinonen et al., 1996) exercises. It should also be noted that the zigzag-type slalom performance alternates the above load virtually onto one leg only (Bauer & Zerpa, 1996), similar to triple jumping.

Considering the triple jumpers' reaction forces of up to 20 times the body weight (Heinonen et al., 2001), the mean polar section moduli at the distal tibia (2369 and 2481 mm^3) in both of our skier groups were even somewhat higher compared with somewhat taller, but equally weighing triple jumpers' mean value (2211 mm^3). This difference in bone strength was mainly because of the skier's more than 0.5 mm thicker cortices at the distal site. Regarding the prevailing notion of the superior osteogenic effect of maximal vertical impact loading, this is a pertinent observation as it suggests an even higher osteogenic potential for rapidly repeated and alternating loadings comprising either moderate vertical impacts or forces from odd directions. However, this does not necessarily apply to long bones shafts. The mechanical rigidity of triple jumpers' tibial diaphysis, a site undoubtedly subjected to very high bending moments during the extreme jumping, was clearly higher compared with our slalom skiers (3197 vs 2594 mm^3), but quite comparable with our moguls skiers (3007 mm^3). It may be that the high bending moments affecting the tibial midshaft in the antero-posterior direction immediately after the landings from high jumps accounted for this. The elongated cross-sectional shape of the midshaft among the moguls skiers (Fig. 3) is also in line with this interpretation.

Compared with the normal erect walking or running position, the typical flexed skiing position in both sports evaluated in the present study makes the associated lever arms longer, which, in turn, increases the bending moments and the consequent loading particularly within the proximal femur. Associated joint moments, taking the incident dynamic muscle forces and lever arms of the body into account, are significant determinants of the structural rigidity of bone (Lovejoy, 1988; Biewener, 1989; van der Meulen & Carter, 1995; Moisio et al., 2004; Nikander et al., 2006). During the vigorous turns in the slalom, the load is virtually exerted on the outer leg only while the hip posture needs to be effectively stabilized by concomitant muscle work (Berg et al., 1995). Then, the associated active muscle force affecting the proximal femur is applied from an unusual (odd) direction contrasting to what occurs during normal, even vigorous bipedal locomotion. Slalom skiing thus seems to impose higher and different loads to the femoral neck compared with moguls skiing (Bauer & Zerpa, 1996; Yee & Mote, 1997; unpublished data, The Research Institute for Olympic Sports, Jyväskylä, Finland, 2005).

Hence, the slalom-induced high loading from an odd direction, exerted alternately on one leg only, may explain the thicker anterior cortex at the femoral neck among slalom skiers, which can be considered to be a relevant finding also from a clinical perspective (Bell et al., 1999b; Mayhew et al., 2005). This finding may offer an important step in the search for a feasible and osteogenic exercise regimen. High-impact exercises are undoubtedly highly osteogenic and can substantially strengthen the loaded bones (Heinonen et al., 1996, 2001; Nikander et al., 2005, 2006), but their feasibility is not so self-evident, particularly among elderly or sedentary people not accustomed to vigorous activity. As it seems possible to strengthen the clinically important femoral neck without intense vertical jumping and consequent high impacts (which may compromise the health of articular cartilage), effective and feasible bone training regimens, primarily based on rapidly alternating, moderate loadings from odd directions are attractive.

This small cross-sectional study naturally has many limitations, and caution must be exercised when interpreting the findings. A small number of world-class skiers in this study provided a relatively weak statistical power to detect small group-differences; thus, the results are suggestive only. With a greater number of skiers, it might have been possible to detect more between-sport differences with statistical significance instead of borderline findings or trends. However, expansion of our study with athletes not being at the top level could also have increased the variance in the bone values. Thus, we decided to include only the very best of the moguls and slalom skiers in our study. It is recalled that one of our main objectives was to compare preliminarily the influence of two distinct loading types on the bone structure at heavily loaded lower extremities, including the unique MRI assessment of the clinically relevant femoral neck cortical structure, at its apparently weakest location (Zebaze et al., 2005). Given the pilot nature of this study, the present findings rather generated interesting hypotheses than proved them, and these hypotheses need to be tested in adequate-powered study designs before final conclusions can be formed.

As regards the athlete studies, the possibility of self-selection bias is always a concern. According to the prevailing notion, genetics can explain even up to 70% of the variance in bone phenotype (Eisman, 1999). To control efficiently the influence of heredity, we should have studied a group of monozygotic twins – one athlete and the other non-athletic control, or in a less optimal design, to expand our study by investigating athletes' first-degree relatives. Given the inherently small sample size of this study, the latter option was not considered appropriate, and the former was impossible due to obvious reasons. On the other hand, recent studies have suggested that the genetic effect on the lower extremity bone strength is not larger than the environmental effect. Hui et al. (2006) concluded that heredity explained about 40% of the variance in femoral neck bone mass, and somewhat more of its area (size), the latter being highly related to body height. Also, in a very recent Finnish twin study, the influence of heredity on the pQCT-derived structural strength indices at the weight-bearing distal tibia and non-weight-bearing radius appeared to be much weaker for the tibia than the radius (30% vs 70%) (Mikkola et al., 2006). It was concluded that the common genes explained a large portion of the compression strength of radius but only a modest portion of the compression strength of tibia, indicating a strong influence of environmental (loading) factors on the structure of weight-bearing tibia.

As the observed between-group differences in the weight-bearing bones were very large, corresponding to even more than two SD above the mean reference level, it is very unlikely that the stronger bone structure of the moguls skiers and slalom skiers could be solely, or even to a large extent, explained by heredity. Likewise, the structural differences observed between moguls skiers and slalom skiers (see Fig. 2 and Table 3) are hardly attributable to heredity; rather, the boys with initially good muscle performance and specific physical abilities were more inclined toward certain athletic activities already in childhood, and thus, they had better opportunity to build strong bones during the period of rapid growth. In our study, this appeared to be the case: all our athletes had started the specific training at younger than 10 years of age, well before the growth spurt. Further, we also observed that among these two athlete groups, the isometric and dynamic muscle performance was virtually identical, the length of the sport-specific training history and the starting age of the career were similar, and also the proportion of weight training and related exercises were the same. Consequently, it seems that the distinct bone structure between the athlete groups was largely dependent on predominant sport-specific loading type.

Taken together, in the world-class male moguls skiers and slalom skiers, the bone structure in the heavily loaded lower extremities was, quite expectedly, very strong compared with normally active referents. The structural strength of their tibiae was attributable to a thick cortex, a high TrD, and a somewhat larger bone cross-section. Further, a particularly noteworthy finding was slalom skiers' thick anterior cortex at the femoral neck. Apparently, the predominant loading type had modulated the skeletal response to physical exertion. Thus, the skeletal loading from odd, lateral directions requiring simultaneous, active muscle work can be osteogenic, the effect being comparable with that received from high-impact vertical jumping. Consequently, it seems possible to develop widely applicable and feasible bone-strengthening regimens, which are not solely based on high vertical impacts.

Perspectives

Mayhew et al. (2005) recently showed that diminished cortical thickness at the inferoanterior–superoposterior axis can predispose the femoral neck to fragility fracture during a sideways fall. Our finding among the slalom skiers suggests that a robust cortex of the femoral neck may also be obtained through odd-impact exercises. These type of exercises, including high bending forces from unusual, lateral directions, may offer an effective way to increase the femoral neck strength without high, potentially harmful, vertical impacts. Commonly practiced odd-impact sports are, for example, soccer and racket-games.

Key words: bone strength, exercise, physical loading, DXA, pQCT, MRI.

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