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Effects of physical activity on bone remodeling

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Abstract

Physical exercise is recommended to improve bone mass in growing children and decrease bone loss in elderly men and women. However, the specific mechanisms by which exercise influences bone metabolism are still not thoroughly understood. The effect of physical activity on the skeleton is generally evaluated by dual-energy x-ray absorptiometry, which measures bone mineral density. However, a relatively long period is needed to detect even a minor variation in bone mineral density with this technique, limiting its usefulness. Bone biochemical markers that reflect the cellular activities of bone formation and resorption are thus also useful tools, both to monitor the acute effects of exercise on bone remodeling and to investigate the mechanisms of exercise-induced changes in bone mass. This article describes the effects of physical activity on bone remodeling in various types of population. The comparison of sedentary individuals and athletes with many years of high-volume sports practice, for example, has clarified some of the long-term effects of exercise. Moreover, the acute variation in bone cell activities after brief exercise or a training program is here examined. The interpretation of results is difficult, however, because of the many parameters, such as age, that are involved. The various populations are therefore categorized to reflect the biological factors implicated in the modulation of bone marker response during exercise.

1. Introduction

The influence of exercise on bone mineral density (BMD) has been extensively evaluated by both cross-sectional [1-3] and intervention studies in young [4] and elderly subjects [5]. Nevertheless, the specific mechanisms by which physical activity influences bone metabolism are still not thoroughly understood. It is widely acknowledged that the bone mass gain from exercise is principally a response to an increase in mechanical strain [6], but other parameters like endocrine changes [7-9] are likely to contribute to the skeletal adaptations. In particular, little is known about the changes in bone turnover induced by various forms of systematic exercise. Because changes in bone mass result from slow-acting metabolic processes, bone biochemical markers should be useful for investigating the acute effects of exercise on bone remodeling. The objective of this work is to focus on the effect of physical activity on bone turnover. For the past 20 years, many studies have investigated these biological parameters. Unfortunately, the conclusions are confounded, probably because no standardized procedures were used. Several factors related to exercise (duration, intensity, or type of exercise), population (young or elderly subjects), and protocol (time points for blood sampling or the use of bone biochemical markers with various specificities and sensitivities) may explain the divergent results. Moreover, it is not clear whether the variation in bone remodeling is an adaptive change associated with long-term training or whether it is an acute effect of a recent exercise bout. Despite the shortcomings of many of the studies to date, this original approach of using bone biochemical markers and calciotropic hormones may elucidate the acute effect of exercise on bone metabolism, which in turn would provide useful information for the design of standardized and adapted therapeutic programs to optimize bone accretion in children and to improve bone health in the elderly.

2. Part 1: bone biochemical markers

By consensus, BMD measurement is used to estimate bone strength and is taken as the primary indicator of a risk of osteoporotic fracture [10]. However, the BMD value

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provides a static representation of bone metabolism; and changes in its value occur at a slow rate. Bone mineral density measurement is thus inadequate to detect slight and acute changes in bone metabolism, such as might occur after a single bout of physical exercise or a training program. Moreover, in confirmed athletes, the relative stability of bone mass during a sports season [11-13] suggests that more sensitive techniques need to be developed to detect minor variations in bone status.

Bone is a dynamic tissue. Under normal conditions, bone resorption and formation are closely coupled in time and space to maintain the integrity of the mass and microarchitecture of the skeleton. This tissue also has the capacity to adapt its structure and function in response to mechanical forces and metabolic demands. For several decades, bone cell activity has been indirectly assessed by bone biochemical markers in urine or serum. As 2 types of bone cell are implicated in the bone remodeling process, osteoblasts that form new bone and osteoclasts that remove old bone, 2 types of markers were developed (Table 1).

One of the biochemical markers of bone formation is osteocalcin (OC), a noncollagenous protein of 49 amino acids predominantly synthesized by osteoblasts and incorporated into the extracellular matrix of bone. A fraction of neosynthesized OC is released into the circulation and can thus be used as an index of mineralization [14]. There have been several OC fragments detected in serum (1-19, 1-43, 20-43, 20-49, 44-49), but their structure and significance remain unclear [15]. More recently, various fragments of OC that were released during degradation of bone matrix and excreted by the kidney have been identified [16]. Urine OC fragments from resorptive origin such as 14-28 are increased in osteoporotic postmenopausal patients and decreased by 27% after only 1 month of alendronate treatment [16], suggesting that this urinary marker may further be used as a marker of bone resorption.

The bone-derived isoenzyme of alkaline phosphatase (B-ALP) reflects a specific measure of the cellular activity of osteoblasts. It is thought to participate in the mineralization process and thus represents bone matrix maturation [17]. During the extracellular processing of type I collagen, the most abundant organic component of the bone matrix, there is a cleavage of the amino-terminal (PINP) and carboxy-terminal (PICP) extension peptides before fibril formation [18,19]; and this reflects osteoblastic proliferation. These markers reflect different stages of osteoblastic development and function.

Two of the biochemical markers of bone resorption are pyridinoline (PYD) and deoxypyridinoline (DPD), both cross-link components that contribute to the stability of the extracellular matrix of bone. Pyridinoline and DPD are released from bone matrix during its degradation by osteoclasts and are excreted into the urine where they can be measured [20]. However, as PYD is also present in other tissues, it is a less specific marker of bone resorption than the carboxy-terminal cross-linked telopeptide of type I collagen (ICTP) [19] or type I collagen C- or N-telopeptide breakdown products (CTX or NTX), which are liberated during the degradation of type I collagen. It was noted that CTX has 2 isoforms: α-CTX contains an Asp-Gly site prone and spontaneously converts to an isomerized form, β-CTX, during bone aging. This finding indicates that the α-CTX/β-CTX ratio might be clinically important in diagnosing metabolic bone diseases [21]. The CTX and NTX on the one hand and ICTP on the other hand reflect various enzymatic mechanisms of collagen type I degradation (cathepsin K for CTX and NTX and matrix metalloproteinases for ICTP) (see the review of Delaisse et al [22]). Moreover, ICTP shows low sensitivity to physiologic variations in bone resorption. Finally, tartrate-resistant acid phosphatase (TRAP) enzyme is expressed in osteoclasts [23].

Bone markers are used to assess dynamic changes in whole bone turnover; and thus, one clinical application is monitoring the effectiveness of antiresorptive treatment in osteoporotic patients. In the context of physical exercise, this type of marker appears to be sensitive enough to determine the bone response to a given exercise and consequently contributes to specifying the effect of exercise on bone. For example, Jurimae et al [12] reported a 16.6% increase in OC in rowers after a 6-month training period without concomitant modification in whole-body BMD. It is possible that bone marker variation precedes the measurable changes in BMD, and this variation may help to estimate long-term skeletal adaptations to physical exercise.

Table 1
Biochemical markers of bone turnover and abbreviations

	Abbreviations	Assay
Markers of bone formation		
Osteocalcin	OC	Blood
Total alkaline phosphatase	t-ALP	Blood
Bone-specific alkaline phosphatase	B-ALP	Blood
Type I collagen extension amino	PINP	Blood
Type I collagen extension carboxy	PICP	Blood
Markers of bone resorption		
Pyridinoline	PYD	Urine
Deoxypyridinoline	DPD	Urine
Carboxyterminal cross-linked telopeptide of type I	ICTP	Blood
Type I collagen C	CTX	Urine/blood
Type I collagen N	NTX	Urine/blood
Tartrate-resistant acid phosphatase enzyme	TRAP	Blood

3. Part 2: bone turnover and physical activity

3.1. Basal bone turnover

3.1.1. In athletes

In parallel to the higher BMD in athletes, higher values for bone formation markers have been found in subjects involved in long-term training in comparison with age-matched controls [7,24,25] (Table 2). Bell et al [7] reported higher OC levels in young men participating in regular

Table 2
Basal bone turnover in adult athletes and controls

Study	Population studied	Training characteristics	Basal bone marker levels
Hetland et al [2]	M R (n = 120; 32 ± 8.1 y)	0-160 km/wk	OC (+32%), DPD (+25%), PYD (+20%) in elite R > CO
	M CO (n = 12; 31 ± 5.8 y)	<5 km/wk	DPD, PYD, t-ALP positively correlated to the weekly distance run.
	M elite R (n = 22; 32 ± 9.2 y)	>100 km/wk	
Bell et al [7]	M muscle-building (n = 14; 24 ± 1 y)	Muscle-building 45 min; 3×/wk	OC (+44%) in exercisers > CO
	M CO (n = 14; 26 ± 1 y)	No regular exercise	
Creighton et al [26]	W high weight-bearing activity (n = 14; 19.9 ± 0.3 y)	10-13 h/wk	
	W medium weight-bearing activity (n = 13; 20.6 ± 0.3 y)	6-14 h/wk	OC in low-impact < high- and medium-impact groups
	W non–weight-bearing activity (n = 7; 19.4 ± 0.3 y)	20 h/wk	Uncoupling index low-impact > medium-impact and CO group
	W CO (n = 7; 22.9 ± 0.6 y)	<1 h/wk	urCTX (NS)
Matsumoto et al [34]	JU (n = 14 M and 23 W; 19.8 and 19.4 y)	National level	DPD in JU > R
	R (n = 24 M and 14 W; 19.5 and 20.4 y)		PYD in JU > SW
	SW (n = 21 M and 7 W; 19.2 and 19.6 y)		B-ALP in M R < M JU and M SW
			PINP (NS)
Maïmoun et al [28]	M CY (n = 11; 27.4 ± 5.8 y)	10.6 h/wk	OC in TR > CO
	M SW (n = 13; 25.5 ± 6.5 y)	10.2 h/wk	OC and CTX in SW > CO
	M TR (n = 14; 25.7 ± 6.6 y)	10.9 h/wk	B-ALP in CY > TR, SW, CO
	M CO (n = 10; 27.5 ± 4.3 y)	<2 h/wk	
Maïmoun et al [29]	13 M decathletes (22.4 ± 2.9 y)	15.5 h/wk	OC (+59.8%), CTX (+41.1%) in decathletes > CO
	13 M CO (25.8 ± 3.3 y)	<2 h/wk	B-ALP (+31.7%, $P = .08$) decathletes > CO
Nishiyama et al [24]	M volleyball players (n = 9; 21.5 y)	2 h/d; 5×/wk	OC (+97%) in volleyball players > CO
	M CO (n = 10; 21.5 y)	No regular exercise	t-ALP (NS)
Karlsson et al [25]	M weight-lifters (n = 19; 25 ± 9 y)	14 ± 6 h/wk	OC (+35%) in weight-lifters > CO
	M CO (n = 19; 26 ± 7 y)	No regular exercise	PICP (NS)
Karlsson et al [30]	M soccer player		
	1st league (n = 24; 22.6 ± 0.6 y)	12 h/wk	OC (+29.6%) and ICTP (+38%) in soccer players > CO
	3rd league (n = 19; 22 ± 0.7 y)	8 h/wk	B-ALP and t-ALP (NS)
	6th league (n = 20; 23.9 ± 0.9 y)	6 h/wk	Bone remodeling increase in soccer players with exercise > 6 h/wk
	M CO (n = 27; 23.3 ± 1.1 y)	<3 h/wk	
Prouteau et al [31]	JU (M, n = 22; 20.9 ± 3.4; W, n = 26; 19 ± 2.4 y)	9.5 ± 3 h/wk	OC in M (+41.5%), in W (+72%) JU > CO
	CO (M, 20.1 ± 1.0; F, n = 12; 19.5 ± 0.9 y)	2 ± 1.5 h/wk	CTX (+25%) in F JU > CO
Brahm et al [32]	Endurance athletes (n = 23 M and 7 W; 32 y)	7 h/wk	PICP (−18%) and ICTP (−22%) in athletes < CO
	CO (n = 23 M and 7 W; 32 y)	No regular exercise	OC and B-ALP (NS)
Ryan et al [81]	W SW (n = 18); R or TR (n = 32) (37 y)	12 h/wk	urNTX (−42%) in athlete < CO
	W CO (n = 21; 41 y)	No regular exercise	B-ALP and DPD (NS)

M indicates men; W, women; CO, control; NS, difference not statistically significant between trained and CO; JU, judoists; R, runners; SW, swimmers; CY, cyclists; TR, triathletes.

muscle-building activity. Similar results were reported in other sports that generate high mechanical strain, such as weight-lifting [25] and volleyball [24]. However, because bone resorption markers were not evaluated, these results do not provide definitive evidence of a beneficial effect of resistance exercise on bone turnover equilibrium. Other studies that focused on both bone formation and bone resorption markers indicated that physically active people present overall accelerated bone turnover [2,26-30]. In elite endurance runners, Hetland et al [2] found higher values of OC, DPD, and PYD, whereas Karlsson et al [30] reported higher values of OC and ICTP in soccer players in comparison with controls. An intense remodeling process was also reported in swimmers [26-28] and decathletes [29]. Prouteau et al [31] reported a higher value for the uncoupling index in female and male judoists compared with control values. Uncoupling index assesses the relative balance of the formation and resorption processes of bone remodeling, and the positive value found in judoists of both sexes indicated a bone metabolic balance in favor of bone formation.

These results contrast with the lower bone formation (−18% for PICP) and resorption (−22% for ICTP) marker levels observed in endurance athletes in comparison with less active controls [32] or the normal B-ALP and DPD and lower urinary CTX reported in highly trained female athletes between 18 and 69 years [33].

Other studies without a reference group could not conclude as to the long-term effects of physical activity [12,34,35] but noted that bone turnover may be affected by the type of training [26,28,34]. Thus, in addition to the mechanical effect of exercise on bone remodeling [26,27], exercise components such as training intensity (strength or endurance) [13,36] and volume seem to be implicated [2,30,37]. Moreover, sex may also modulate bone and collagen marker response [13,38].

Osteopenia is an established health risk for female distance runners with chronic amenorrhea [39]. Zanker and Swaine [40] reported lower bone turnover, particularly lower bone formation, in female runners with chronic amenorrhea (>4 years) compared with eumenorrheic counterparts and eumenorrheic sedentary controls. In other studies, bone turnover was not affected [41] despite lower spinal BMD in the amenorrheic group in comparison with eumenorrheic [41,42] and sedentary [42] groups. These data seem to suggest that the process at the origin of the bone loss in amenorrheic athletes is not the same as the process observed in postmenopausal women. In these women, an increase in bone turnover is due to estrogen deficiency [40]. Because amenorrhea seems to particularly affect the lumbar spine, the bone turnover status of the rest of the skeleton may mask a localized imbalance [42].

The exercise effects on bone turnover markers in the growing skeleton have received little attention, and the effects on bone formation markers are controversial. Some studies reported no effect of exercise on OC, total ALP (t-ALP), or B-ALP [43,44] and PICP or PINP [44-46]. Others showed either significantly higher [47,48] or lower [46] bone formation marker concentrations in exercising subjects compared with controls. Concerning the markers of bone resorption, higher urinary or serum CTX [45,48,49] and normal [44,46,50] concentrations have been reported. These studies were principally conducted in young gymnasts of both sexes who consistently presented higher BMD or stronger bone than the less active controls [43,44,46-51]. In this specific young population, the modification in bone markers induced by growth [52] or by delayed growth as a result of strenuous exercise [53] may partially mask the effect of physical activity [44].

The cross-sectional studies evaluating the long-term effects of exercise on bone turnover in athletes nevertheless seem to have some limitations such as small samples sizes. Moreover, as noted by Whipple et al [54], the serum samples were collected in the midst of active training programs, making it uncertain whether the modifications in bone marker values reflected the acute response to a recent exercise bout or a chronic variation. Evaluation of bone turnover in athletes should therefore intervene only after a minimum of 24 hours of recovery [54].

3.1.2. In retired athletes

One fundamental question about the effects of exercise on bone metabolism is the following: Is the BMD gain over the span of a sports career maintained in retirement? Few studies have investigated the residual benefits for bone turnover. Karlsson et al [30] reported no difference between former soccer players and age-matched controls in terms of bone remodeling, but they found 39% lower OC and 69% lower ICTP in the retirees than in active soccer players. Similar results were reported in retired weight-lifting athletes [37]. These data seem to indicate that athletes who reduce their training reach a new steady state of bone remodeling equivalent to that of sedentary subjects.

3.1.3. In elderly subjects

In comparison with less active controls, endurance-trained postmenopausal women present higher BMD at the lumbar spine and radius but similar bone remodeling despite lower serum estrone [55]. This suggests that the positive effect of exercise on bone mass may not be due to altered rates of turnover but rather to higher serum 1.25 $(OH)_2D$ levels, which increase intestinal calcium (Ca) absorption, or to higher growth hormone and insulin-like growth factor–1 levels, which may act on bone as anabolic growth factors [55].

In the general population, the effects of physical activity on bone remodeling appear to be less clear than in athletic populations. Studies have reported a favorable effect [56-58] or no effect [59-61]. It is likely that bone markers are able to discriminate only populations with very different levels of physical activity, as suggested by the results of Theiler et al [62]. Their study demonstrated a difference in bone remodeling status only between institutionalized patients and physically active ambulatory subjects but not between moderate- and high-inactivity groups.

3.2. Long-term effects of physical activity on bone turnover

3.2.1. In athletes

As demonstrated by various studies [11-13] (Table 3), bone mass in adult athletes remains relatively constant over the 6- to 12-month sports season, probably because the bone tissue is accustomed to the mechanical loading generated by the repetition of similar types of exercise [6]. However, given that bone biochemical markers probably respond more quickly to exercise than bone mass, several authors attempted to identify a variation in bone remodeling after a relatively short period of training. Recently, Sartorio et al [35] evaluated the bone markers in athletes over an entire sports season, which entails periods of training, competition, recovery, and resting. No significant variation in ICTP values was observed over the 6 months of follow-up in either sex, whatever the sport. Similarly, other studies reported minor variations (ranging from 15% to 20%), which were probably partially attributable to the high biological variability of bone markers [11-13]. Soccer players, however, showed a decrease in bone formation (PICP, t-ALP) and an increase in bone resorption (ICTP) within 4 weeks of reduced activity during the recovery period between 2 sports seasons [63]. This may indicate that a

Table 3
Long-term effects of physical activity on bone turnover

Study	Population studied	Initial training characteristics	Exercise evaluated	Timing analysis	Change in bone markers
In children					
Eliakim et al [4]	M training group (n = 20; 16 y)	Not defined	2 h/d, 5×/wk: aerobic training (90%) and resistance training (10%) during 5 wk	Before and after 5 wk	In trained subjects: OC (+15%), B-ALP (+21%), PICP (+30%) ↑ UrNTx (−21%) ↓ DPD (=), urCTx (=)
	M CO (n = 18; 16 y)				In CO: no variation
Nichols et al [47]	W GY (n = 11; 19 ± 1.2 y)	4 h/d; 5 d/wk	Habitual training	Before and after 27 wk	OC (=)
	CO (n = 11; 21.1 ± 2.1 y)	<3 h/wk		Not evaluated	
Daly et al [43]	M GY (n = 31; 10.1 ± 0.2 y)	16.4 h/wk (range, 10-29)	Habitual training	Before and after 3, 6, 9, 12, 15, and 18 mo	OC ↑ (+21.5% in CO and +50% in GY) t-ALP (=)
	M CO (n = 50; 9.4 ± 0.2 y)	No regular exercise			
Nickols-Richardson et al [50]	W GY (n = 4; 10 ± 0.3 y)	15.7 ± 1.6 h/wk	Habitual training	Before and after 6 mo	PYD, DPD ↓ in GY and CO OC/DPD ↑ in GY and CO
	W CO (n = 8; 10.1 ± 0.3 y)	No regular exercise			
In adults					
Woitge et al [36]	M aerobic training (n = 10; 25.3 ± 2.6 y) M anaerobic training (n = 10; 23.5 ± 2.9 y) M CO (n = 12; 25.3 ± 2.7)	<1 h/wk	Aerobic or anaerobic training program 60 min/d; 3×/wk during 8 wk	Before and after 4 and 8 wk	Aerobic group: B-ALP and OC ↓ at wk 4 and (=) at wk 8 PYD and DPD ↓ at wk 4 and wk 8 Anaerobic group: B-ALP, OC, and PYD ↑ at wk 8
Karlsson et al [63]	M soccer players (n = 12; 22.8 ± 1.2 y)	12 h/wk	Habitual training	Just before the end of soccer season, and weekly for 4 wk of resting period and after 10 d of restart training	PICP ↓ at 2-4 wk of resting period
	M CO (n = 27; 23.4 ± 1.1 y)	No regular exercise			t-ALP ↓ at 3 and 4 wk of resting period and restart training ICTP ↑ at 4 wk of resting period OC (=)
Fujimura et al [68]	M training group (n = 8; 26.4 ± 1.2 y) M CO (n = 7; 24.6 ± 1.0 y)	No regular exercise	Weight training program 45 min/d; 3×/wk during 4 mo	Before and after 1, 2, 3, and 4 mo of training	OC (+26.3%) and B-ALP (+30%) ↑ in trained PICP (−18%) ↓ in CO DPD (=)
Etherington et al [69]	M military recruits (n = 40;18.5 ± 1.6 y)	10 wk of military training	Habitual training	Before and after 10 wk	OC ↓ ($\log_{10}$ OC −11.6%), B-ALP ↓ (−13.6%) TRAP (=)
Casez et al [70]	M military recruits (n = 140; 20-22 y)	Good physical condition	15 wk of military training	Before and after 15 wk	OC (+8.3%), t-ALP (+14.7%) ↑

(*continued on next page*)

Table 3 (*continued*)

Study	Population studied	Initial training characteristics	Exercise evaluated	Timing analysis	Change in bone markers
Maïmoun et al [11]	M TR (n = 7; 19.2 y)	15 h/wk	Habitual training	Basal and after 32 wk	B-ALP ↓ (−22%) OC, CTX (=)
Jurimae et al [12]	M rowers (n = 12; 20.8 ± 3.0 y)	Relative rest period: 11.6 h/wk Training period: 16.8 h/wk	Habitual training	Before and after 6 mo	OC ↑ (+16.6%)
Sartorio et al [35]	M (n = 25; 22 ± 4 y) W (n = 22; 22 ± 5 y) Regionally or nationally ranked athletes	2-3 h/d for 4-5×/wk	Habitual training	Basal value at the start and after 2, 4, and 6 mo	ICTP (=)
In elderly					
Menkes et al [5]	M trained (n = 11; 59 ± 2 y) M CO (n = 7; 55 ± 1 y)	No regular exercise	16 wk strength training; 3×/wk	Before and after 12 and 16 wk of training	Variation in trained subjects only OC ↑ at 12 and 16 wk (+19%) B-ALP ↑ at 16 wk (+26%) TRAP (=)
Yamazaki et al [73]	W trained (n = 27; 64.2 ± 2.9 y) W CO (n = 15; 65.7 ± 2.7 y)	No regular exercise	1 y of walking; 1 h/session; 4×/wk at 50% of Vo_2max	Just before and after 1, 3, 6, 9, and 12 mo in the trained and every 6 mo in the CO	In trained group: B-ALP ↓ (~20%) after 12 mo ur NTX ↓ (~25%) after 3-12 mo OC (=) In CO group: urNTX (=)
Sartorio et al [76]	M trained (n = 16; 72.9 ± 0.95) M CO (n = 14; 73.3 ± 1.04)	45-60 min light to moderate daily physical activity	16 wk high-intensity strength training, 3×/wk	Before and after 16 wk	B-ALP ↑ (+31.7%) and ICTP ↓ (−6%) in trained OC, PINP (=) in trained and CO
Vincent and Braith [77]	M and W HRG (n = 22; 66.6 ± 7 y) M and W LRG (n = 22; 67.6 ± 6 y) M and W CO (n = 16; 71 ± 5 y)	No regular exercise	6 mo, 30 min/d; 3×/wk. Training at 80% of their 1-RM Training or at 50% of their 1-RM	Before and after 6 mo	OC ↑ LRG (+25.1%) and HRG (+39%) B-ALP ↑ (+8%) in HRG PYD (=) Ratio OC/PYD HRG > LRG > CO Ratio B-ALP/PYD HRG > LRG and CO
Ryan et al [81]	M trained (n = 21; 61 ± 1 y) M CO (n = 16; 59 ± 2 y)	No regular exercise	16 wk strength training, 3×/wk	Before training and after 16 wk of training	TRAP ↑ in trained and CO OC, B-ALP (=)
Remes et al [83]	M trained (n = 70; 57 ± 2.9 y) M CO (n = 70; 57.8 ± 2.8 y)	No regular exercise	4 y of aerobic exercise; 3×/wk, 30-60 min/session at 40% to 60% of ventilatory aerobic threshold	Basal and after 1 and 4 y	After 1 y, TRAP in trained < CO After 4 y (NS) OC (NS; =) after 1 and 4 y

GY indicates gymnasts; ↑, an increase compared with pretraining values; =, no change compared with pretraining values; ↓, a decrease compared with pretraining values; HRG, high-resistance intensity group; LRG, low-resistance intensity group.

new steady state in bone turnover was achieved after a few weeks of reduced activity [63] and would partly explain the faster BMD loss observed in former athletes [46].

As mentioned (see the chapter on basal bone markers in athletes), the effect of physical activity on bone may be masked in growing children; and longitudinal studies are thus more appropriate for this population. Nickols-Richardson et al [50] reported no difference in basal values between gymnasts (n = 4) and controls (n = 8) in a small population of young subjects. After 6 months, a similar decrease in bone resorption markers was observed in the 2 groups, whereas OC increased in the athletes and decreased in the controls. This difference was suggested as an explanation for the higher bone gain in the gymnasts [50]. A specific bone adaptation to exercise is nevertheless not always found to be associated with a specific bone remodeling process [43].

3.2.2. In young sedentary individuals

Peak bone mass was shown to be the major factor influencing the development of osteoporosis [64]; and consequently, under routine conditions, its improvement is a practical strategy to prevent osteoporosis later in life. Several authors have thus attempted to demonstrate that a physical activity program might be applied to increase peak bone mass.

In young subjects, 5 to 8 weeks of endurance-type training seems to improve bone remodeling in favor of formation because it reduced bone resorption activities [4,36,65] and only transiently reduced [36,66] or increased [65] bone formation activities. In contrast, anaerobic or resistance training induced an overall acceleration in bone turnover [36] or an increase in bone formation associated with a decrease [67] or no variation [68] in bone resorption. These results suggest that a relatively brief training program in untrained young subjects might modify bone turnover in favor of bone accretion. However, exercise intensity seems to play a crucial role in the type of bone cell response. Moreover, as the variation in bone cell activities may be transient, at least a few months of training are probably needed to stabilize the bone remodeling.

Army recruits provide a unique opportunity to study a homogenous group of subjects undergoing rapidly progressive and weight-bearing physical activity. Etherington et al [69] reported that 10 weeks of training induced a decrease in bone formation markers (OC and B-ALP) with a nonsignificant decrease in TRAP. In contrast, 15 weeks of military training induced an increase in OC and t-ALP in a similar population [70].

In premenopausal women, 5 months of resistance exercise training resulted in a posttraining increase in OC concentration; and this value remained elevated for 18 months [71].

3.2.3. In postmenopausal women and elderly subjects

Exercise programs have been suggested as countermeasures against involutional bone loss in postmenopausal women or elderly subjects, but this method remains a great challenge. To date, little has been done on bone turnover despite the strict dependence of bone mass on the balance between bone formation and bone resorption.

Studies investigating the long-term effects of training programs have shown a reduction [72-74], an increase [5,75-77], or no change [78-83] in bone formation markers after periods ranging from 4 months to 4 years in postmenopausal women and older men. These biological modifications were associated with a favorable effect [5,73,74,78,81,82] or no effect [33,80] on BMD. At the same time, a reduction [73,83] or no change [5,76-79,81] in bone resorption markers was also reported. A positive effect on bone is the maintenance of BMD in subjects after an exercise program in comparison with bone loss observed in controls [73] or a direct increase in BMD [5,72,74,77,79,81]. In middle-aged men, Remes et al [83] reported a reduction in TRAP 5b activity in the exercise group in comparison with the reference group after 1 year of exercise, but not after 4 years. These results suggest that the maximal effect of exercise on bone resorption occurs early in the course of the adaptation to training and that continued training without increased intensity does not result in further adaptation. Similarly, a favorable temporary effect was also reported after 6 months but not after 1 year of high-impact aerobic exercise in postmenopausal women [84].

Determining the most osteogenic training program for elderly populations is not a straightforward proposition, as suggested by the divergent results on key points from 2 studies that used an identical procedure [5,81]. In elderly men, a 16-week strength training program stimulated bone formation but did not modify bone resorption and induced a 2% BMD gain at the lumbar spine and a 3.8% gain at the femoral neck [5]. The same group also reported a 2.8% BMD increase at the femoral neck but no effects on bone turnover [81]. Except for the initial BMD difference between the 2 studies, no specific factors were identified that would explain the discrepancy in bone marker findings because the training regime, sex, and age of the subjects were nearly identical.

Moreover, in addition to the type of training (endurance or strength), training intensity seems to play an important role in the response of bone markers to exercise [77]. In elderly men and women, Vincent and Braith [77] reported a better effect of high-intensity (80% of 1-repetition maximum [1-RM]) than low-intensity (50% of 1-RM) resistance exercise, as demonstrated by the magnitudes of change in the OC/PYD or B-ALP/PYD ratio after 6 months of training. These biological results were confirmed by a BMD gain at the femoral neck (+1.96%) only in the high-intensity group. In a randomized study, Hatori et al [79] observed a gain in lumbar spine BMD in women who trained (30 minutes 3 times per week for 7 months) above the anaerobic threshold and a decrease in those performing the same type of training but below the anaerobic threshold and in controls. Nevertheless, no variation in bone markers (OC and

hydroxyproline: a nonspecific marker of bone resorption) was observed in the exercise group, whereas the markers increased in controls. The effect of exercise intensity was not confirmed in another study, which found no variation in OC level or BMD after 12 months of high- and low-intensity resistance training [80].

3.3. Short-term effects of physical activity on bone turnover

3.3.1. In athletes

Although it has been well demonstrated that prolonged mechanical loading through physical activity increases bone mass, brief exercise at low or high intensity does not seem to have an immediate measurable effect on bone turnover in active subjects [85], athletes [24,86-88], untrained individuals [89-91], or active or sedentary elderly subjects [92] (Table 4). Kristoffersson et al [88] reported no modification in markers of formation (PICP, OC) or resorption (ICTP) in 7 ice hockey players just after a modified Wingate test and after 60 minutes of recovery. Virtanen et al [86] found no change in serum PICP concentration in well-trained young men just after a single bout of high-intensity concentric muscle work, but noted a significant decrease after 1 hour. Two days after exercise, PICP started to increase significantly; and this persisted to the end of the experiment at 96 hours, possibly reflecting a late adaptive process in bone as observed in other studies [24,89,90]. Exercise that exceeds 20 to 30 minutes thus seems to be required to induce an immediate variation in bone markers. This is particularly observable after marathon running, an activity that combines long duration (>2 hours) and high intensity. During this type of exercise, a decline in bone formation markers (OC and B-ALP) was observed just after the race and also after 3 to 5 days of recovery, without modification in urine hydroxyproline [93]. Crespo et al [94] reported an increase in t-ALP and a decrease in TRAP after the same type of exercise. These variations persisted after 24 hours of recovery. In a study with similar design, PICP transiently decreased just after a marathon, increased to a peak at day 3 postexercise, and returned to basal level at day 5, whereas ICTP increased immediately after the race [95]. Various hypotheses were advanced to explain the primary decrease in PICP. It may have been due to an increase in PICP clearance by the kidneys [32] or, alternatively, to the temporary inhibition of collagen synthesis by the intensive mechanical loading [86]. Moreover, the apparent suppression of osteoblast activity may also be related to the overproduction of glucocorticoids during highly physical activity [93], as this molecule inhibits osteoblast function in vivo and decreases serum OC levels. Our group did not confirm this last observation during a 50-minute cycling test [96].

A maximal exercise test, which is shorter than the marathon but of greater intensity, induced no variation in OC and PINP levels but increased ICTP values with a peak at the end of exercise in elite athletes of several sports [97]. This modification was followed by a subsequent decrease to baseline level or below within 2 hours. No variation in ICTP just after a running test until exhaustion was reported in well-trained men and women, whereas OC levels increased only in women who also presented lower basal values [98]. After a 30-minute ergometer cycling exercise (warm-up and 20 minutes at 80% maximal oxygen uptake [V_{O_2}max]), bone formation (t-ALP, PINP) and bone resorption (PINP) markers, with the exception of OC, transiently increased or remained elevated (ICTP) in 17 male athletes [99], suggesting an overall acceleration in bone turnover. In a similar protocol but lasting 60 minutes, only an increase in CTX was observed after 30 minutes of recovery, with a peak after 60 minutes [100]. The uncoupling of bone formation and resorption during an endurance non–weight-bearing activity may explain the low BMD at the lumbar spine of athletes like cyclists [101,102]. In a more recent study, a parallel transient rise in CTX, OC, and B-ALP was also reported during cycling exercise performed at 75% of V_{O_2}max. However, all the markers returned to basal values during the recovery period [96]. Last, Zittermann et al [103] reported that a moderate 60-minute run at 70% of maximal speed induced a reduction in PICP levels after 3 hours of recovery without modification in CTX.

3.3.2. In young or adult sedentary individuals

In physically untrained individuals, the majority of studies report no immediate variation in bone markers after endurance training, defined as 30 minutes of brisk treadmill walking [91] with or without additional weight [104] and 45 minutes of running at 50% of V_{O_2}max [90]. In contrast, Nishiyama et al [24] and Rudberg et al [105] reported, respectively, an increase in OC levels after 30 minutes of running on ergometer at 50% of maximum capacity and an increase in B-ALP isoform B2 after moderate jogging for 30 to 40 minutes. None found a concomitant variation in t-ALP [24] or ICTP and OC [105]. In parallel with these results, Rong et al [106] reported an increase in OC after 45 minutes of endurance cycloergometer exercise at 55% of V_{O_2}max, but not after 15 minutes of a similar exercise at 85% of V_{O_2}max. No acute variation in ICTP was observed in either situation.

No immediate bone marker variations were demonstrated in any of the studies on strength training. These studies included various repetition sets at 50% to 80% of 1-RM [89,107]. Only Brahm et al [108] reported an increase in PICP and B-ALP associated with a decrease in OC after a 30-minute incremental 1-leg knee extension exercise.

However, it may be that the response of bone markers is delayed, as observed in trained subjects. This is suggested by an increase [90,91] or decrease [54,89,106,107] in bone resorption markers associated with an increase [90], a decrease [107], no variation [54,91,106], or normalization [24] of bone formation markers 1 to 32 hours after the end of the exercise. Moreover, after 24 hours of recovery, t-ALP increased in the group of “brisk walking with additional weight-lifting,” whereas the marker decreased in the group of “walking alone” [104]. This was interpreted as an anabolic

Table 4
Short-term effects of physical activity on bone turnover

Study	Study population	Training characteristics	Exercise evaluated	Timing analysis	Change in bone markers
Nishiyama et al [24]	M volleyball players (n = 9; 21.5 y) M CO (n = 10; 21.5 y)	2 h/d; 5×/wk No regular exercise	30 min of running at 50% of their maximum capacity	Just before and after exercise and 60 min of recovery	OC ↓ in volleyball players after 60 min of recovery OC ↓ in CO only just after exercise
Whipple et al [54]	M nontrained (n = 9; 21.9 ± 1.2 y)	<60 min/wk	45 min (3 sets of 10 repetitions for 7 resistance exercises at 50%-75% of the 10-RM	Just before; just after; and 1, 8, 24, and 48 h of recovery	B-ALP and PICP (=) sNTX ↓ 1 and 8 h of recovery urNTX (=)
Maïmoun et al [85]	M and W (n = 18; 71.7 y) active M an W (n = 18; 71.9 y) less active M and W (n = 9; 25.8 y) active	Vo_2max_{th}: 154% Vo_2max_{th}: 136% >3 h/wk	Maximal exercise test (Vo_2max)	Just before and just after exercise	OC, B-ALP, CTX (=)
Kristoffersson et al [88]	M ice hockey players (n = 7; age, 22 y)	Highly trained	Modified Wingate test: duration, 30 s	Before the test and after 5 and 60 min of recovery.	PICP, OC, ICTP (=)
Ashizawa et al [89]	M (n = 10; age, 24.3 ± 0.9 y)	No regular exercise	3 sets of 10 repetitions for 7 resistance exercises: 1 set at 60% of 1-RM and 2 set at 80% of 1-RM	60 min before the test; just after the test; and 15, 45, 105, and 165 min after the test	DPD ↓ after 105 min
Thorsen et al [90]	W (n = 14; 25.2 y)	No regular exercise	45 min running at 50% of Vo_2max	15 min before the test and after 1, 24, and 72 h of recovery	PICP ↓ after 1 h and ↑ after 24 and 72 h of recovery ICTP ↑ after 24 and 72 h of recovery OC ↑ after 1 h of recovery
Welsh et al [91]	M (n = 10; 25.7 y)	<1 h/wk	30 min of walking at 60% of HRmax	Before the test; just after; and after 0.5, 1, 8, 24, and 32 h of recovery	B-ALP (=) and OC (=) Pyr (+25.1%), D-Pyr (+28.9%) ↑ on day 2 of recovery
Maïmoun et al [92]	M (n = 11) and W (n = 10; 73.8 y)	Active: 151% of the Vo_2max_{th}	Maximal exercise test (Vo_2max)	Just before and just after exercise	B-ALP, OC, CTX (=)
Malm et al [93]	M (n = 8; 29.9 y) runners W (n = 15; 40.3 y) runners	M: 44 km/wk W: 52 km/wk	Marathon running	Day 10; just after marathon; and 1, 3, and 5 d later.	OC ↓ in M and W after marathon and after 1, 3, and 5 d (only in W) B-ALP ↓ in W after marathon and until 5 d Hydroxyproline (=)
Crespo et al [94]	M elite runners (n = 11; 26 y) W elite runners (n = 7; 28.2 y)	150-210 km/wk 100-150 km/wk	Marathon (42 km running)	5 min before, just after the marathon, and after 24 h of recovery	t-ALP ↑ at the end of the race and after 24 h TRAP ↓ at the end of the race and after 24 h
Langberg et al [95]	M (n = 17; 31.8 y)	No data	Marathon (42 km running)	1 wk before; just after the race; and after 1, 2, 3, 4, 5, and 6 d of recovery	PICP ↓ (−13%) after the race ↑ peak after 3 d (+12%) and after 5 d (=) ICTP ↑ (+ 46%) after the race and after 24 h (=)

(*continued on next page*)

Table 4 (*continued*)

Study	Study population	Training characteristics	Exercise evaluated	Timing analysis	Change in bone markers
Maïmoun et al [96]	M cyclists (n = 7; 24.4 y)	16.3 h/wk	2× 50 min at −15% of VT (−VT) and +15% of VT (+VT)	Just before; after 30 and 50 min of exercise; and after 15 min of recovery	B-ALP ↑ at 30-50 min at −VT and +VT, (=) after 15 min OC ↑ and CTX ↑ at 30-50 min at +VT, (=) after 15 min
Ehrnborg et al [97]	M (n = 84), W (n = 33) 25 y	National or international level	Maximal exercise test (Vo_2max)	−30 min; just before the test; just after; and at 15, 30, 60, 90, and 120 min after exercise	ICTP ↑ with a peak at the end of exercise, (=) at 120 min OC and PICP (=)
Wallace et al [99]	M athletes (n = 8, 28.3 ± 2.8 y) with GH treatment M athletes (n = 8, 25.5 ± 1.5) with placebo	>4×/30 min sessions/wk	30 min incremental cycle exercise; 5 min at 1 W/kg, 5 min at 2 W/kg, and 20 min at 80% of Vo_2max	−60 min, −30 min and just before exercise and at 15-min intervals during 2 h after the start of the exercise	OC (=) B-ALP (+7.4%), PICP (+9.2%) ↑ at the end of the exercise ICTP ↑ at the end of the exercise and remain elevated thereafter (+7%)
Guillemant et al [100]	M TR (n = 7; 30.7 y)	6-12 h/wk	60 min at 80% Vo_2max on cycle ergometer	−60 min, −30 min, and just before the test 30 and 60 min during the test 30, 60, 90, and 120 min of recovery	Ca supplementation: CTX (=); B-ALP (=) No Ca supplementation: CTX ↑ until 120 min of recovery; B-ALP(=)
Zittermann et al [103]	M (n = 18; TR, game sports, 25.2 ± 0.6 y)	15.7 ± 1.7 h	60-min run at 70% of maximal speed or 60-min rest	1 h before exercise and after 3 h of recovery	PICP (−9.8%) ↓ only during exercise CTX ↓ during exercise and rest (biologic fluctuation)
Tosun et al [104]	W (n = 9; 28.2 y)	Sedentary	Brisk walking 30 min at 60%-85% of the HRmax with (WE) or without (E) additional weight (5 kg)	Just before, after 30 min of exercise, and after 15 min of recovery. t-ALP after 24 h	OC, PICP, PINP, ICTP (=) t-ALP ↑ for WE and ↓ for E at the 24th h ICTP ↓ in all exercises after 4 h of rest
Rong et al [106]	M (n = 8; 23 ± 3 y)	Noncompetitive physical training 2 h/wk	Test on cycle ergometer at 55% of Vo_2max for 45 min (E55%) or at 85% of Vo_2max (E85%) for 15 min Strength exercise at 85% of 3-RM Same scheduled without exercise	Just before; during the last minutes of exercise and CO; and after 1, 4, and 24 h of recovery	OC ↑ E55% DPD ↓ (−27 %) after 3 d; TRAP ↓ (−15%) after 1 d
Ashisawa et al [107]	M (n = 14; 24.5 y)	No regular exercise	3 sets of 10 repetitions for 7 resistance exercises: 1 set at 60% of 1-RM and 2 set at 80% of 1-RM	Before exercise; just after; and 1 and 3 d of recovery	PICP ↓ (−12%) after 1 d; B-ALP ↓ (−13%) after 2 d and (−9%) after 3 d; OC (=)
Brahm et al [108]	M (n = 6), W (n = 6); age, 23-36 y	No regular exercise	30 min incremental 1-leg knee extension exercise (10 min warm-up, 15 min at 60% of peak Vo_2max and 5 min at peak Vo_2max)	Before the test and after 5 and 60 min of recovery	PICP and B-ALP ↑ just after exercise and (=) at 60 min of recovery OC ↓ just after exercise and (=) after 60 min of recovery ICTP ↓ after 60 min of recovery

Brahm et al [115]	M (n = 10), W (n = 10); age, 21-46 y	Vo_2max 46.7 mL/(min kg) in W, 56.2 mL/(min kg) in M	35 min incremental running exercise at 30%, 47%, 76%, and 100% of Vo_2max	Before the test and after each load (each 10 min), after 30 min and 24 h of recovery	OC adjusted to plasma volume ↓ (−13.6%) just after exercise and ↑ (+8.3%) after 24 h of recovery PICP adjusted, t-ALP ↑ after 24 h of recovery
Zanker et al [120]	M runners (n = 8; age, 25.1 y)	50 km/wk	2 sessions of 60-min running for 3 d with 100% of their estimated daily energy requirement (balance) or 50% of this value (restricted)	For plasma: the day of the 1st exercise and the day before the last exercise For urine: the day before exercise and the last day of exercise	Balance condition OC, PINP, DPD, urNTX (=) Restricted condition DPD, urNTX, OC (=)
Grimston et al [125]	W runners (n = 16) W CO (n = 6)	>50 km/wk <3×/wk	45 min of submaximal exercise	Just before and after exercise and 45 min of recovery	With or without Ca supplementation OC (=)

HRmax indicates maximal heart rate; VT, ventilatory threshold; GH, growth hormone treatment; Vo_2max_{th}, theoretical Vo_2max.

effect of the additional weight. However, only t-ALP, a nonspecific marker of bone formation, was affected by this type of exercise [104].

3.3.3. In postmenopausal women and elderly subjects

After a maximal walking test lasting 8 to 13 minutes, no significant variation in bone turnover was observed in elderly and moderately or highly active subjects [85,92]. This may be attributable to the low ground reaction forces generated by brisk walking [109] and the short duration of the exercise, as well as the short period of postexercise investigation. Similarly, no variation was observed in OC in a group of late postmenopausal women after a single episode of brisk walking, whereas PICP increased only after 24 and 72 hours of recovery [110]. The decrease in ICTP at 1 hour was followed by an increase at 72 hours. Intense cycling exercise (a non–weight-bearing exercise) by postmenopausal women induced a rapid increase in serum concentrations of B-ALP isoforms B1 and B2 [105]. It is probable that the presence of enzyme in the osteoblast membranes made its release into blood easier in comparison with ICTP and OC, which were not modified after the exercise. Zerath et al [111] reported an increase in OC levels after a maximal exercise test before a 6-week training program but not after. The difference in response was not related to a variation in basal values.

3.4. Factors implicated in the modulation of bone marker response during exercise

3.4.1. Biological factors

The mechanism for direct postexercise variation in bone markers is probably multifactorial. Exercise induces an increase in lactate concentration accompanied by the generation of an equivalent number of protons that acidify the intracellular and extracellular environments [87,89,112]. Metabolic acidosis is known to stimulate osteoclastic activity and thus increase ICTP concentrations [113] and to concomitantly suppress osteoblastic activity [114]. However, in various studies, bone marker levels were reduced after exercise, suggesting that other factors like mechanical loading reduced bone resorption [107]. Another contribution may come from long-term training, with years of exercise performance causing microdamage to bone and muscle with leakage to the blood. Moreover, some of the changes might be due to the effect of hemoconcentration in response to exercise [115], although a more recent study demonstrated that the net changes in markers of bone and collagen turnover in response to acute exercise exceeded those attributable to changes due to hemoconcentration [99]. The modification in bone resorption markers may also be related to a decrease in serum Ca levels because Ca supplementation during exercise was found to completely suppress the exercise-induced rise in CTX [100]. In addition, a decrease in bone markers may be related either to diminished bone formation or resorption activity or to increased kidney clearance [108]. Last, the basal values of bone markers also seem to affect the response [91,92,98].

3.4.2. Other factors

In addition to the variations related to the type of exercise, other factors that might influence bone marker response to exercise include age [99,116], sex [93,98,116], training [24,115], contraceptive use [117], and nutritional status [31,100,118-120].

3.5. Limitations in using bone biochemical markers

In the field of exercise, the expectation was that bone markers would provide information not given by dual-energy x-ray absorptiometry. It was thought that the initial variation in these markers would predict subsequent changes in BMD, although this has not been clearly demonstrated [13]. Until now, only Yamazaki et al [73] reported a moderate negative correlation between the percentage change in urinary NTX level at months 3 and 12 and lumbar BMD at month 12 after a walking program. It is probable that the predictive potential of bone markers will need to be demonstrated over a long follow-up period in an extensive population, which is not generally the case in evaluations of training programs. Moreover, bone formation and resorption markers represent an average of the turnover in all skeletal sites and, thus, are not site specific [26]. As previously demonstrated, physical activity induces a bone gain at the mechanically loaded site [3,121]; and a moderate BMD gain would not be highlighted by a variation of bone markers.

3.6. Specific recommendations for using bone biochemical markers

In studies using bone markers to evaluate the direct effect of physical activity on bone metabolism, all the biological factors that affect their variability, such as sex, age [122], and circadian or seasonal variations [123], must be controlled. Long-term studies should systematically include a control group to suppress seasonal variation [123]. When the study period is shorter, 2 similar evaluations (timing, duration, position of the participants) during 2 sessions with and without exercise should be studied. The importance of this is particularly well illustrated by the parallel marked reduction in serum CTX levels during both rest and exercise testing [103].

The timing of blood sampling is particularly critical. To evaluate the acute effect of a recent exercise bout, but not the remaining effect related to the training program, Whipple et al [54] recommended that blood samples be collected at least 24 hours after the bout. Moreover, a standardized procedure that takes into account the effects of diurnal variation (similar time of evaluation) and food intake should be developed [120]. In fact, given the biological variability of these markers, a single measurement may be inadequate to fully assess bone turnover levels [13].

Prolonged intense exercise elicits a biphasic response of plasma volume. This is characterized by hemoconcentration during exercise followed by hemodilution not exceeding 10% in the 12 to 48 hours postexercise [124]. As the effect of plasma volume on bone marker variation has not been completely determined [115], hematocrit should be systematically analyzed.

Investigation should also be continued into the recovery period to take into account the delayed responses of bone turnover, as the acute effect seems to be relatively limited [24,54,86,89-91,107,115].

Most studies have investigated only one activity of bone cells, principally bone formation [7,24,25]; and as an imbalance between bone cells activities was not excluded, simultaneous evaluation of bone formation and bone resorption markers is thus needed. In addition, the majority of studies highlighted the need for a combination of 2 or more markers to fully characterize each bone activity [68] to reflect the different stages in osteoblastic cell proliferation and function or collagen maturation.

4. Conclusion

Bone biochemical markers may become very attractive tools for investigating the immediate response of bone cells to exercise, particularly in the aim of individualizing exercise programs to improve bone health. However, typical responses to different types of exercise have been difficult to obtain up to now, probably because many factors like sex and physical fitness modify the responses. Moreover, it is currently unknown whether the variations measured in these markers were partially due to changes in metabolism and/or clearance. Nevertheless, bone markers may contribute to elucidating the processes of bone turnover and the effects of different types of athletic training. Crucial data are still needed on how exercise affects bone biochemical markers so that they can be optimally used in the sports context. In particular, an important issue is whether early exercise-induced variations in bone turnover can be used to predict future bone mass gain. Lastly, several points have been highlighted from this review of the relevant studies: (1) Athletes undergo a bone remodeling process that is generally accelerated in comparison with that of sedentary subjects. Nevertheless, the type of training and its various components (ie, weight bearing, impact, aerobic, and anaerobic) may modify the level of bone turnover. (2) High-training subjects seem to have relatively stable bone remodeling during the sport season, whereas in untrained subjects, a physical activity program modifies the osteoblastic and/or osteoclastic functions over the long term. In any case, the modification remains dependent on the type of training. (3) Exercise does not seem to have a noticeable short-term effect on bone turnover, and monitoring during the recovery period is necessary to detect minor variations.

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