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Bone Mineral Content Distribution in Response to Long-term Training of Elite Rowers

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Abstract. *Background/Aim: Bone response to exercise depends on the type and size of the mechanical stimulus. In rowing, athletes are exposed to low mechanical but large compression loads mainly on the trunk. Thus, this study aimed to investigate the impact of rowing on total and regional bone quality and bone turnover parameters in elite rowing athletes vs. control subjects. Materials and Methods: Twenty world-class rowers and twenty active, but not athletic, men participated in the study. Bone mineral density (BMD) and body mineral content (BMC) were assessed by dual-energy X-ray absorptiometry (DXA). Bone turnover markers (OPG and RANKL) in serum were assessed by Elisa method. Results: The current research revealed no statistical difference in total bone mineral density (TBMD) and total body mineral content (TBMC) between elite-level rowers and control subjects. Nevertheless, Trunk BMC (p=0.02) and Trunk BMC/TBMC ratio (p=0.01) were significantly higher in rowers than those in the control group. In contrast, in the control group, the Lower limbs BMC/TBMC ratio (p=0.007) was statistically higher. Furthermore, RANKL (p=0.011) and OPG (p=0.03) were statistically significantly higher in rowers, whereas the OPG/RANKL ratio (p=0.012) was statistically higher in the control group. Conclusion: Rowing, as a non-weight-bearing exercise, did not alter total bone density but induced a remarkable redistribution of bone density from the lower limbs to the trunk. In addition, the current evidence suggests that the underlying molecular mechanism is based on turnover of intermediates, rather than solely bone redistribution.*

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It is widely acknowledged that the gravity and magnitude of the load applied to specific skeleton sites determine the bone mass density (BMD) rather than exercise and movement per se (1). According to Wolff's law, bones can alter the amount and distribution of bone mass in response to the applied forces (2). The redistribution of bone mass does not arise overnight but occurs over a lengthy process and depends on the frequency, intensity, and length of time the stimulus is applied on the bone (3).

Bone response to exercise depends mainly on the type, duration, frequency, and intensity of the mechanical stimulus. Mechanical forces that act on the bone are generated from impact with the ground (ground-reaction forces) and from skeletal muscle contractions (muscle forces or muscle-joint forces). Based on these principles, regional skeletal response is expected to be different based on the type of exercise performed (4). Therefore, bone mineral density is influenced by diet, hormones genetic predisposition and the type of physical activity performed (5). More specifically, various comparative studies between athletes and control groups indicate significant differences in bone density, which can reach up to 40-50% depending on the sport and type of bone (6). It seems that the differences occur mainly in the bones that are exposed to mechanical loads. For example, in elite tennis players, the bone density of the hand holding the racket is much higher compared to the other hand (7). Similar differences have also been observed in the bone density of the footballers' legs (8). The bones of the arms are denser and stronger in sportsmen whose activities include mainly training of the upper part of the trunk, such as rugby, climbing, kayak, and weightlifting (7, 9). In contrast, the legs' bone density is higher in athletes whose activities include short-distance running and muscle strengthening exercises. However, no improvement or effect on bone mass is observed in sports without mechanical loads, such as long-distance running or swimming (10).

Research on aquatic sports is scarce, and water is dealt with as a non-weight bearing medium, with controversial outcomes on bone health benefits. Various lower impact aquatic sports may not improve the osteogenic effect observed with land exercise; however, they appear to protect from disuse bone loss and preserve bone quality (11). The impact on site-specific bone density depends on the intensity and force exerted by a load or exercise (1, 12). Studies supporting this with exercise in the water are gradually emerging. Postmenopausal women trained with weight-bearing aquatic training exhibited equal benefits on bone mineral density to those trained with land resistance exercises instead of sedentary women (13). However, certain types of aquatic sports' effect on bone remodeling remain unclear as specific groups of athletes have not yet been studied thoroughly. A characteristic example is rowing, a non-weight-bearing sport, like swimming and cycling. The significant difference of rowing exercise in respect to other sports in the same category is that the athletes are exposed to low mechanical loads, much like the athletes of other non-weight-bearing sports are exposed to but are also exposed to much larger compression loads mainly on the trunk, which does not occur in other sports. Studies on BMD in response to rowing are very limited when considering bone markers and bone remodeling and re-distribution. For instance, in a study in elite heavyweight female rowers examining the fluctuations of training load during an Olympic year, although inflammation markers responded to fluctuations in training load, BMD and bone mineral content remained stable during the season, suggesting that training load periodization was not harmful to bone health (14).

Furthermore, the trunk to total body BMC has not been (extensively) studied and is a new concept in rowing. A major role of the trunk is to serve as a means to transmit the power generated from the legs and hips to the arms and into the oar, which serves to propel the boat. This comparison was selected based on the specific kinesiology of rowing, which is characterized by the forward and backward loading movement of the trunk that often causes trunk injuries in the lower back (15). More specifically, rowing propulsion forces are distributed between the lower and upper body of the rower; rowing forces are exerted on the rower's foot, rowing seat and on his hands, and there is direct connection between foot stretcher force and oar handle force (16). The comparison between trunk and lower extremities was done for investigative purposes, but it was conceived based on observations on rowers' trunk bone mass distribution following exerted propulsion forces.

Furthermore, bone metabolism markers are used in several studies to evaluate dynamic changes in the turnover of bone redistribution (17). In the context of physical activity, the bone markers seem to be sufficiently sensitive so that one can specify bone's reaction to a particular exercise, thus contributing to the determination of the effect of exercise on bone density (18). The identification of the osteoclastogenesis inducer, the receptor activator of nuclear factor-kappaB ligand (RANKL), its cognate receptor RANK, and its decoy receptor osteoprotegerin (OPG), has contributed to the significant advance in the understanding of the molecular mechanisms involved in the normal physiology of the skeleton. Indeed, the ratio of OPG/RANKL reflects the balance between the two bone markers (*i.e.*, OPG promoting bone formation and RANKL promoting bone absorption), and this phenomenon is due to the greater increase in the denominator (RANKL), which as a result leads to increased osteoclastogenesis (19). In addition, changes in serum OPG and RANKL may be acute (up to one month) or chronic (12 months and more), which may reflect and explain the underlying molecular pathway. Given that this molecular pathway is considered to be a mechanism involved in exercise-induced bone remodeling and the fact that, to our knowledge, no other study so far has examined the implication of these bone markers in rowing, we aimed at evaluating their role in the present study.

In this respect, the current research investigated the long-term effect of rowing on bone density in elite rowers. This study aimed to investigate the impact of rowing exercises on total and regional bone quality, by comparing elite rowing athletes to a control group. Specifically, we aimed to examine the theory of redistribution of bone content based on the load originated from the impact of rowing exercise. The investigation was performed by investigating the relationship of total bone density and bone content to the corresponding peripheral sections and by examining specific biomarkers of bone metabolism.

Materials and Methods

Participants. Twenty elite rowers and twenty physically active but not athletic men participated in the study. The elite rowers were in the middle of the Olympic Cycle and the measurements took place in Spring. According to the McKey grading system (20) for athletic status, 4 of the rowers were in tier 5 (World Class Category) and the rest 16 were in tier 4 (Elite/International Level), whereas eight off them were in the lightweight category and the other twelve were in the open weight category. In addition, the elite rowers had been actively training for over eight years and had participated in more than six national or international championships. It is important to note that these athletes have competed with significant distinctions both at the Olympic Games and in international and European tournaments. The control group consisted of twenty healthy, active, but not athletic men that did not smoke with a sedentary lifestyle.

Table I. *Anthropometric characteristics of the participants.*

	Rowers	Control group	*p*-Value
N	20	20	
Age (y)	27.4±5.8	29.9±5.5	0.163
Body mass (kg)	79.1±8.9	83.6±9.5	0.132
Height (cm)	181.3±6.9	179.6±5.3	0.379
Percent fat (%)	14±5.3	24.3±5.1	**0.001**
Fat mass (kg)	11.3±49	20.5±5.9	**0.001**
Muscle mass (kg)	64.5±6.4	56.8±13.3	**0.026**

Bold values indicate statistical significance.

Table II. *Total and regional bone mineral content (BMC).*

	Rowers	Control group	*p*-Value
Total BMC (g)	3,560±409	3,383±435	0.19
Upper limbs (g)	481±67	455±61	0.21
Lower limbs (g)	1,316±151	1,295±182	0.70
Trunk (g)	1,257±161	1,127±185	**0.02**
Upper limbs BMC/ Total BMC	0.135±0.01	0.134±0.01	0.27
Lower limbs BMC/ Total BMC	0.37±0.01	0.38±0.02	**0.007**
Trunk BMC/ Total BMC	0.35±0.01	0.33±0.02	**0.01**

Bold values indicate statistical significance.

Study design.

Experimental protocol. The participants were asked to come in the lab after 12 hours fast, be sufficiently hydrated, and refrain from exercising 24 hours before the examination. All measurements took place in the early morning hours, between 07:30 and 10:00 am.

Body measurements. Initially, anthropometric characteristics of the participants, such as height and body weight, were recorded. Height was determined with a Seca Wall Mounted Stadiometer (Model 222, Germany). In contrast, body weight was determined with a standard graduated Seca 767 Digital Column Scale (Germany) to the nearest 0.1 cm and 0.1 kg, respectively. The participants wore light clothing, while footwear was removed during the measurements. DXA body composition was collected as described below in the bone density assessment section.

Bone mineral content and bone mineral density assessment. Body bone mineral content (BMC) and bone mineral density (BMD) were measured by dual-energy X-ray absorptiometry (DXA) (Model Lunar DPX, Lunar Corp., Madison, WI, USA). Standard DXA protocols were followed. Bone sections were defined as head, arms (right and left), spine, pelvis, ribs, leg (right and left), and trunk (right and left). All measurements were performed by the same person, an experienced exercise physiologist specifically trained in DXA operation, participants positioning, and data management. Before performing the measurements, DXA was calibrated daily for quality assurance purposes. All scan files were analyzed by the same technician using the Lunar software (version 4.7e) (GE Lunar, Madison, WI, USA). Italian population values were used as reference. Total BMD and BMC were measured with a precision (coefficient of variation) of 0.7%.

Bone biomarkers. Fasted blood samples were taken from an antecubital vein without stasis. ELISA method was used for the quantitative determination of human OPG and human ampli-sRANKL in serum samples of the participants by the Biomedica Gruppe immunoassay kits (Biomedica Medizinprodukte GmbH & Co KG, Wien, Austria).

Statistical analysis. Preliminary power calculation analysis verified that the sample size of 20 rowers and 20 control subjects assured an adequate power to detect statistical significance.

Continuous variables are presented as mean±standard deviation, whereas qualitative variables are presented as absolute values or frequencies (%). *T*-tests were employed for the comparisons of continuous variables between the two groups. Statistical significance alpha level was set a-priori at 0.05. The measurements were analyzed by the SPSS software (SPSS 26 Corp., Chicago, IL, USA).

Study approval. The institutional review board approved the study. All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. The researchers obtained written informed consent of the participants, who were thoroughly informed about the purpose of the research and their right to remove their consent at any stage of the investigation.

Results

The anthropometric characteristics of the participants are shown in Table I. In most body parts, total bone mineral density (TBMD) and total body mineral content (TBMC) did not differ between the elite rowers and the control group. However, Trunk BMC (p=0.02) and Trunk BMC/TBMC ratio (p=0.01) were statistically higher in rowers than those in the control group. In contrast, Lower Limbs BMC/TBMC ratio (p=0.01) was statistically higher in the control group (Table II). The percentage differences between the control group and rowers concerning the peripheral bone parts of lower limbs over the total bone mass [Lower Limbs BMC (g)/Total BMC (g)] was less by 3.5%, whereas concerning the trunk over the total bone mass Trunk BMC (g)/Total BMC (g)] was greater by 6.1% (Figure 1). We have used the trunk BMC/total BMC and upper and lower limbs BMC/total BMC ratio, because in our study, it confers a more detailed and accurate result, as it allows the concomitant evaluation of peripheral *vs*. total sections and reflects better the effect of rowing on the body. Additionally, there was a statistically significant difference between elite rowers and the control group concerning the measurements of BMC/BMD of the trunk (p=0.007) (Table III). Rib BMD and BMC were also evaluated but there were no statistically significant differences between rowers and controls.

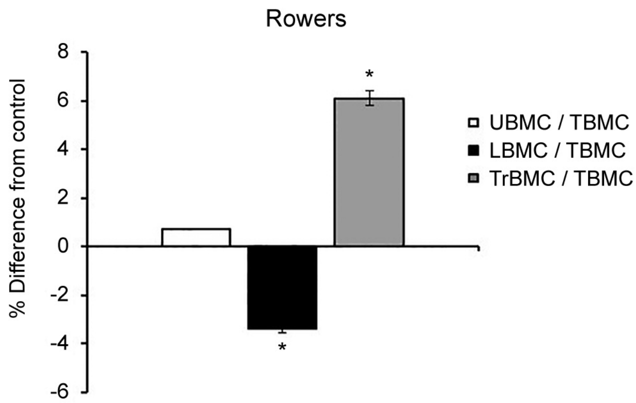

Figure 1. *Difference (%) between Control group and rowers in upper limbs bone mineral content (UBMC) (g)/total bone mineral content (TBMC), in lower limbs bone mineral content (LBMC)/TBMC, and in trunk bone mineral content (TrBMC)/TBMC. Statistical significance: p<0.05.*

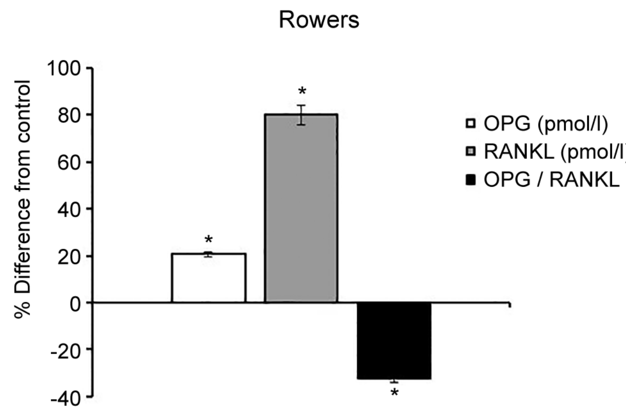

Figure 2. *Difference (%) between Control group and rowers in bone metabolism markers Osteoprotegerin (OPG), receptor activator of nuclear factor-kappaB ligand (RANKL) and OPG/RANKL ratio. Statistical significance: p<0.05.*

Table III. *Total and regional bone mineral content/bone mineral density.*

	Rowers	Control group	*p*-Value
Total (cm^2)	2,773±238	2,687±221	0.24
Upper limbs (cm^2)	463±50	456±46	0.64
Lower limbs (cm^2)	909±95	928±97	0.54
Trunk (cm^2)	1,168±107	1,072±105	**0.007**

Bold values indicate statistical significance.

Table IV. *Bone metabolism markers concentrations (pmol/l).*

	Rowers	Control group	*p*-Value
OPG (pmol/l)	6.29±1.22	5.22±0.76	**0.030**
RANKL (pmol/l)	0.09±0.04	0.05±0.04	**0.011**
OPG/RANKL ratio	86.3±42.6	127.5±52.2	**0.012**

Bold values indicate statistical significance. OPG: Osteoprotegerin; RANKL: receptor activator of nuclear factor-kappaB ligand.

Finally, elite rowers had statistically significant differences in the values of bone markers (increase in OPG levels by 21%, p=0.03 and increase in RANKL levels by 80% (p=0.011). The opposite effect was observed in the ratio of OPG/RANKL in elite rowers, which was 32.3%, statistically significantly lower compared to that of the control group (p=0.012) (Table IV, Figure 2).

Discussion

The current study results showed that rowing might increase BMD at site-specific bone areas. More specifically, rowing is associated with an apparent redistribution of bone mass from the lower limbs to the trunk, also reported for other sports like water polo (21). Moreover, biochemical markers demonstrated that bone remodeling was more evident in rowers than those in the control group. Indeed, our data showed that even though the serum levels of both features were higher in rowers, RANKL levels were found even higher, indicating substantial rates of bone resorption. Furthermore, no statistical differences were found in TBMD or bone density at specific skeleton sites between elite rowers and the control group. A possible explanation is that rowing belongs to the non-weight-bearing low-impact sports. As a result, the bone structure does not receive loads that could elicit different adaptations compared to the general population.

Interestingly, the current study demonstrated a considerably higher bone density in the trunk of rowers as opposed to the control group, in contrast to the values of bone density of the limbs, where no differences were recorded. This can be explained by the position of the rower's body on the rowing vessel and the rowing movement, which compresses the trunk by the sliding seat and pushes leg action, which can create loads on the trunk that would possibly elicit specific bone density gains in that area. Even though rowers use their legs more, the high compressive loads are transferred to the trunk and benefit it, as demonstrated by the higher bone density in the area at the expense of the limbs, where no bone density shifts were recorded. It is noteworthy that the ratio of bone density of the trunk to total bone density was increased, whereas the corresponding ratio of the lower limbs was decreased. Thus, a redistribution of bone density from the lower limbs to higher parts of the body, mainly the trunk area, was observed.

The present study's data did not demonstrate any association between the molecular indices and bone density (BMD). The fluctuation of bone markers possibly precedes the measurable changes in bone density, and this difference can aid in evaluating long-term skeletal adaptation to physical activity. The current study's findings are in conjunction with those of other researchers. Morel *et al.* (9) studied the relationship between specific sports and their effect on bone mass; this study involved 704 men who participated in 14 different types of amateur level sports and were 30. The results showed that rowers and swimmers had low total BMD and low peripheral BMD in their feet. The lack of gain in BMD and BMC in aquatic sports, without showing their losses, is not necessarily a negative outcome. Non-weight-bearing activities may create a better environment for bone preservation than that observed in weightlessness is, a space where bone loss may be detrimental and non-reversible on many occasions (22). It was also found that total BMD was greater in weight-bearing sports compared to non-weight-bearing ones. Five weight-bearing sports had the highest total BMD: rugby, football, bodybuilding, combat sports, and other team sports. In contrast, two non-weight-bearing sports had a low total BMD: swimming and rowing.

Nevil *et al.* (7) studied bone density in 106 male athletes compared with control groups in nine different sports. Their research revealed that the low-strain, low-impact activities of rowing and cycling failed to benefit BMD compared with the age-matched controls. The authors suggest that sporting activities involving high impact, physical contact and/or rotational forces or strains are likely to convey significant benefits not only to the loaded sites, but also to other unloaded peripheral and axial sites throughout the skeleton. Jürimäe *et al.* (18) examined the effect of 6 months of training on bone metabolism in elite rowers. The results showed that the formal preparatory training period in elite rowers failed to show differences in BMD and BMC, suggesting that bone mass remains relatively constant during the preparatory period. Only the peripheral BMD of the hand area showed a statistically significant difference, which is probably due to the higher training loads. In other studies, bone density among rowers was found to be higher compared to other endurance athletes such as triathletes (1, 23) cyclists (1, 24), swimmers (1, 25) but similar to runners (26, 27) in specific skeletal areas that sustain loads during training. This further reinforces the importance of the impact of the activity on bone growth. Unlike previous research, Cohen *et al.* (28) found a significant increase in the average BMD of the lumbar spine (2.9%) and of the average BMC (4.2%) in young rowers that participated in college-level competitions during a seven-month training period in rowing. In addition, studies in women rowers at the college level showed that the coaching period significantly increases BMD of the lumbar spine (29, 30). Finally, Lundy *et al.* (31) demonstrated that BMD of elite rowers appears to fall mainly within the optimal range for the general population; however, lightweight rowers tended to have lower BMD than their heavyweight counterparts at all measured sites of the spine and for females also at the femur.

Finally, indices of bone marker metabolism (OPG and RANKL) demonstrate that bone remodeling is enhanced in rowers compared to the control group. It is possible that this increase functions as a rebound mechanism due to exercise.

Limitations. A vital concern of the researchers was the appropriate choice of individuals so that eventually, the sample would be homogeneous and representative for each test group. The rowers were members of the national rowing team with long experience (8 years), high-performance standards, and many international distinctions (*e.g.*, Olympic Games and international competitions). Although the researchers can ascertain that the experimental group is a representative sample, the same cannot be said about the control group, even though it was randomly selected from the population based on the criteria presented above.

Conclusion

Rowing as a non-weight-bearing exercise, did not alter total bone density, but induced a remarkable redistribution of bone density from the lower limbs to the trunk. Despite increases in the concentration of both bone metabolism markers, OPG and RANKL, the decrease in the OPG/RANKL ratio in rowers suggests that bone remodeling process is more activated in rowers and that the underlying molecular mechanism is based on bone resorption, clearance, and turnover of intermediates, rather than solely on bone redistribution.

Conflicts of Interest

SAK is a scientific consultant for Hyduro Inc. and has active grants with Danone Research and Standard Process. The rest of the Authors report no conflicts of interest in relation to this study.

Authors' Contributions

MSP: Methodology, investigation, formal analysis and interpretation, writing-original draft preparation. KSA and RT: Conceptualization, supervision, methodology, investigation, writing-original draft preparation. VS: Data analysis and interpretation. SH: Methodology. BKN: Data analysis and interpretation. SLS: Methodology, investigation.

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