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Resrach article

Nordic Walking Increases Distal Radius Bone Mineral Content in Young Women

Takeru Kato [1,4]✉, Toru Tomioka [2], Takenori Yamashita [3], Hidehiro Yamamoto [1], Yasuhiro Sugajima[1] and Norikazu Ohnishi [5]

[1]Asahi University, Department of Health Science and Sports Sciences, School of Health Sciences, Mizuho, Gifu, Japan; [2] Meijo University, Faculty of Foreign Studies, Nagoya, Aichi, Japan; [3] Suzuka University of Medical Science, Faculty of Health Sciences, Department of Clinical Radiation, Suzuka, Mie, Japan; [4] Suzuka University of Medical Science, Faculty of Health Sciences, Department of Clinical Nutrition, Suzuka, Mie, Japan; [5] Mie Prefectural College of Nursing, Faculty of Nursing, Tsu, Mie, Japan

Abstract

Unlike the lumbar spine and femur, the radius does not bear a gravitational mechanical compression load during daily activities. The distal radius is a common fracture site, but few studies have addressed the effects of exercise on fracture risk. The aim of this study was to determine the effects of the pole push-off movement of Nordic walking (NW) on the bone mineral content (BMC) and areal bone mineral density (aBMD) of the distal radius and the muscle cross-sectional area (CSA) at the mid-humeral and mid-femoral levels. The participants were allocated to two groups: an NW group and a control group. The NW group walked at least 30 min with NW poles three times a week for six months. There were no significant changes in muscle CSA at the mid-humeral or mid-femoral levels between or within groups. There were also no significant changes in BMC or aBMD at 1/3 and 1/6 of the distance from the distal end of the radius in either group. However, the BMC and aBMD at 1/10 of the distance from the distal end of the radius were significantly increased by NW. The NW pole push-off movement provided effective loading to increase the osteogenic response in the ultra-distal radius. The ground reaction forces transmitted through the poles to the radius stimulated bone formation, particularly in the ultra-distal radius.

Key words: Non-weight-bearing bone, muscle cross-sectional area, ground reaction force, dual energy x-ray absorptiometry, magnetic resonance imaging.

Introduction

Osteoporosis is a disease that reduces bone mineral content (BMC) and leads to deterioration of bone structure. The lower bone strength leads to a higher risk of fracture (National Institute of Health (NIH), 2000). After menopause, bone fragility increases and fractures can occur, which can limit daily activity and reduce quality of life, particularly in the older population. The NIH has reported that hip and vertebral fractures are a problem for women in their late 70s and 80s, while wrist fractures are more common in patients in their late 50s to early 70s (NIH, 2000). The distal radius is also a common site of fracture.

Nordic walking (NW) was first described in Scandinavia as a Nordic skiing training method during the summer of 1930. NW was further developed and was later introduced in Europe as a modern sport around 1990 (Tschentscher et al., 2013). NW is a walking fitness exercise that uses specially designed poles. When walking using poles, as in cross-country skiing, the pole push-off movements involve placing pressure on the ground through the poles while swinging the arms. There is evidence that 12 weeks of NW improves overall health and cardiovascular metabolism (Church et al., 2002), increases high-density lipoprotein concentration and reduces low-density lipoprotein and triglyceride concentrations (Hagner et al., 2009) and increases the walking distance during a 6-min walking test in patients with cardiovascular disease (Girold et al., 2017). The driving force against the ground produced by the pole push-off movement during NW increases walking speed (Church et al., 2002) and stimulates muscle activity in both arms (Shim et al., 2013; Sugiyama et al., 2013; Pellegrini et al., 2018).

Adaptation to bone mechanical stress is site-specific (Kohrt et al., 1997; Bass et al., 2002; Kontulainen et al., 2002; Dowthwaite et al., 2012; Duckham et al., 2014; Umemura et al., 1997; Umemura, 2016; Hart et al,, 2017) and mechanical stress that acts as a reaction force in the direction of gravity increases bone strength (Kohrt et al., 1997; Umemura et al., 1997). Unlike the femur, the radius does not have a gravitational mechanical compression load when ground reaction forces are transmitted from the ground during daily activities (Kohrt et al., 2009; Robling, 2009). We therefore wished to focus on the efficacy of NW pole push-off for stimulating osteogenesis in the distal radius. In the present study, we aimed to determine the effects of a 6-month NW program on the BMC and areal bone mineral density (aBMD) of the distal radius and the cross-sectional area of the muscle at the mid-humeral and mid-femoral levels, measured using dual-energy x-ray absorptiometry (DXA) and magnetic resonance imaging (MRI), respectively.

Methods

Participants and exercise program

Ethics approval for this study was obtained from the ethics committee at the Mie Prefectural College of Nursing (reference number 110401) and the procedures were conducted in accordance with the institutional guidelines. The purpose and all experimental procedures were carefully explained to each participant and written informed consent was obtained prior to their enrollment in the study. One hundred and twenty-seven healthy female college students were asked to take part in the study and 41 students (21.5 ± 1.8 yrs) volunteered to participate. The inclusion criteria

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were: no contraindications to exercise, no pregnancy, eumenorrhea, non-smoker, no regular training except swimming and walking and no medical or surgical conditions likely to affect bone metabolism. We used questionnaires that have previously been used in similar age groups (Kato et al., 2006; 2015). The 41 healthy female college students were randomly allocated to two groups, using the random number function of MS Excel 2013: NW (n = 21) and control (n = 20) groups. A menstrual cycle questionnaire was completed twice, at baseline and immediately after the 6-month NW training period. At the end of the training period, two participants were excluded from the NW group because of irregular menstruation (menstruation occurred on fewer than nine occasions during the 12 months preceding the end of the NW training period). Two participants were also excluded from the control group because they began regular resistance training after the NW training intervention, which included arm and wrist curls using dumbbells three times a week. Therefore, data from 19 NW and 18 control participants were analyzed.

We prepared the NW poles (Leki, Supreme titanium) by adjusting the pole length and exchanging the replacement rubber grip (Leki, walking rubber chip), following the instructions of an International NW Federation coach. The NW group participants used the same poles throughout the intervention periods. The NW group participants walked for at least 30 min, but not more than 60 min, using the NW poles three times a week for 6 months at a target rating of perceived exertion of 10–11. The NW group participants walked for 30 min during the first month, for 5-to-10 min longer during the second month and for a further 5-to-10 min longer during the third month. The NW group participants walked in groups as much as possible, along sidewalks near the university they attended and selected the walking routes themselves. These routes were relatively flat and even and the surfaces were frequently hard, so that there was relatively little slip when the NW pole came into contact with the walking surfaces. Prior to the intervention, participants in the NW group were instructed and trained by an International NW Federation coach. All 21 of the NW group completed 6 months of NW training. The participants in the control group were asked to perform similar normal daily activities to those they performed before the study and all 20 completed the measurements at baseline and after the intervention period.

Dietary intake was assessed using a 3-day food diary 1 month before initiating the NW training, across 2 weekdays and 1 weekend day. The participants recorded their menus on each day, listing each ingredient and its approximate mass. These food records were checked by a dietitian and nutrient intake was analyzed using Eiyokun version 4.0 software (Kenpakusha, Tokyo, Japan) and a standard Japanese food database. Participants who consumed less than 650 mg/day (the recommended calcium intake; Japanese Ministry of Health, Labour and Welfare, 2015) of calcium received nutritional counseling and were subsequently reassessed using a second 3-day food diary. Participants who consumed less than 500 mg/day were administered calcium carbonate supplements as 300 mg tablets to be taken with meals during the intervention.

Dual energy x-ray absorptiometry (DXA) measurement

aBMD, BMC and muscle cross-sectional area (CSA) were measured by a single nationally registered and qualified radiological technologist, both before and after the intervention, who was blinded to the group each individual belonged to. A DXA (DCS-3000, Aloca, Japan; analysis software ver. 5.00) scanner was used to make measurements 1/10, 1/6 and 1/3 of the length of the radius of the non-dominant arm from the distal end, according to the manufacturer's instructions (Figure 1). The BMC (g) and area (cm^2) were measured to determine the aBMD (g/cm^2). Forearm length was measured by the DXA operator using a measuring tape, from the styloid process of the radius to the lateral epicondyle of the humerus. After the position of the styloid process of the radius was fixed in the DXA scanner, the distances from the distal end of the radius were calculated automatically. The same forearm length was used for measurements at baseline and after the intervention.

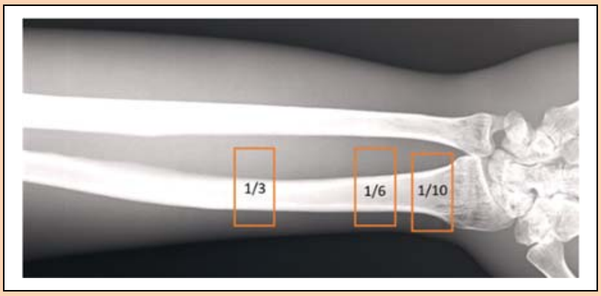

Figure 1. Representative scan of the distal radius. The three analyzed regions (boxed insets) 1/3, 1/6, and 1/10 of the bone length from the distal end of the radius. Measurements were performed using the software supplied by the manufacturer (DCS-3000, Software Ver. 5.0, Aloka, Japan).

Although the measurement sites and the age of the participants differed, the short-term coefficients of variation of the BMC and aBMD measurements were 2.0% and 0.9% for the lumbar spine (n=9) and 2.8% and 2.0% for the femoral neck (n=13), respectively (Kato et al., 2009), when the same instrument, protocol and operator were used.

We did not estimate the coefficients of variation of the BMC and aBMD measurements in the younger participants (21.5 ± 1.8 yrs), because of the greater x-ray exposure required. The aBMD measurement had an in-house precision error of 1.0% (Aloka, Japan), on the basis of the adult scans. The DXA machine was calibrated daily using a phantom calibration procedure and no significant drift was apparent during the study.

Magnetic resonance imaging (MRI) analysis

The muscle CSA at the levels of the non-dominant mid-humerus and left mid-femur was measured using a 1.0-T MRI (Magnex αII, SMI-50C, Shimadzu, Japan). The CSA at the level of the mid-femur was obtained at the midpoint between the greater trochanter and the lateral epicondyle of the femur. A single operator measured, recorded and marked the midpoints of the femur and humerus before and after the intervention period. The CSA was also measured at the level of the mid-humerus, at the midpoint between the greater tubercle and the lateral epicondyle of the humerus. Participants were scanned using a T1-weighted spin-echo sequence with 8 mm slice thickness, 20 ms echo time, 610 ms repetition time and a 256 × 256 matrix. Scion Image for Windows (Scion Corporation, USA) was used to calculate the muscle CSA at the mid-humeral and mid-femoral levels. The cross-sectional area of the cortical bone, the periosteal and endosteal perimeters of the femoral bone and the cross-sectional area of the muscle were measured in scans using Scion Image for Windows software (Scion Corporation, USA), which is based on NIH Image for Macintosh (National Institutes of Health). Repeated measurements made using this system yielded a coefficient of variation of 3.0% for muscle (Kato et al., 2015).

The triceps and biceps brachii muscles were assessed, instead of the forearm flexor muscles. This was because if the Nordic walker grasped the NW poles firmly, the arm would bend and the NW poles would be placed in front of the intended position. As a result, the landing impact forces were in the direction of walking. The International NW Federation coach instructed the participants to avoid this movement and instead to generate a driving force with the NW pole push-off by not holding the NW poles tightly. In addition, a strap was attached to the NW pole grip, so that the participants did not have to grip the NW pole.

Statistical analysis

The mean baseline physiologic characteristics, anthropometric measures of the humerus and femur and mean heart rate during walking were compared between the NW and control groups using unpaired Student's *t*-tests. A two-way analysis of variance (ANOVA, NW/Control × baseline/after intervention) with repeated measures was used to compare the BMC and aBMD at each site along the radius, the muscle and adipose CSAs at the mid-femoral and mid-humeral levels and calcium intake. When ANOVA revealed a significant interaction (group × time), Bonferroni-adjusted paired *t*-tests were performed to determine the differences between the baseline and post-intervention values in each group. Statistical comparisons were compared using a statistical analysis package (SPSS, version 15.0J, SPSS Japan). The significance level was set at 0.05 and all comparisons were two-tailed.

Results

The physiologic characteristics of the participants are summarized in Table 1. There were no significant differences in age, height, or body mass between the two groups. There were also no significant differences in the lengths of the humerus or femur between the NW and control groups.

One month before the NW intervention, the mean daily calcium intake of the participants, calculated using the food diary, was 546.0 ± 136.4 mg/day (n = 37). Although this is well above the mean daily calcium intake of 428 ± 236 mg/day for Japanese women in this age group (Japanese Ministry of Health, Labor and Welfare, 2017), it is still below the recommended calcium intake of 650 mg/day (Japanese Ministry of Health, Labor and Welfare, 2015). Therefore, after analyzing the food diaries, participants who consumed less than 650 mg/day of calcium received nutritional counseling and were asked to repeat their 3-day food diary. In addition, participants who consumed less than 500 mg/day (n = 10; NW group = 4, control group = 6) were administered calcium carbonate supplements as 300 mg tablets, which were consumed with meals during the intervention and this increased the daily elemental calcium intake to 634.6 ± 74.2 mg/day for the NW group and 607.0 ± 84.5 mg/day for the control group. There was no significant difference in calcium intake between the NW and control groups.

There were no significant changes in BMC or aBMD 1/3 and 1/6 of the way along the radius from the distal end in either group during the study. However, the BMC and aBMD 1/10 of the way along the radius had significantly increased in the NW group after the intervention (Figures 2 and 3). Furthermore, there were no significant changes in muscle or adipose CSA at the mid-humeral and mid-femoral levels between baseline and the end of the study in the NW group (Figures 4 and 5).

The Nordic walkers' participation rate had a mean of 83.5% throughout the intervention period. This compliance level is slightly higher than that achieved in our previous high-impact and low-repetition jumping intervention study that was conducted in participants of a similar age (Kato et al., 2006).

Table 1. The physiologic characteristics of participants in the NW and control groups. Values are means ±SDs.

	Control (n = 18)		NW (n = 19)	
	Baseline	Post-intervention	Baseline	Post-intervention
Age (years)	21.4±0.6		21.2±0.8	
Height (cm)	1.58±0.07	1.58±0.06	1.60±0.05	1.61±0.05
Weight (kg)	51.1±6.1	51.0±6.5	51.2±4.6	51.1±4.8
BMI	20.7±2.0	20.5±2.1	19.9±2.1	19.9±2.1
Length of humerus (cm)	27.9±2.2		28.6±2.4	
Length of femur (cm)	43.3±7.4		44.5±6.0	
Periosteal perimeter of mid-numerus (cm)	6.5±1.0	6.5±0.6	6.5±0.9	6.7±0.9
Calcium (mg)	507.2±143.5	607.0±84.5**	571.4±125.2	634.6±74.2**

** significant difference between baseline and post-supplementation calcium intake ($p < 0.01$).

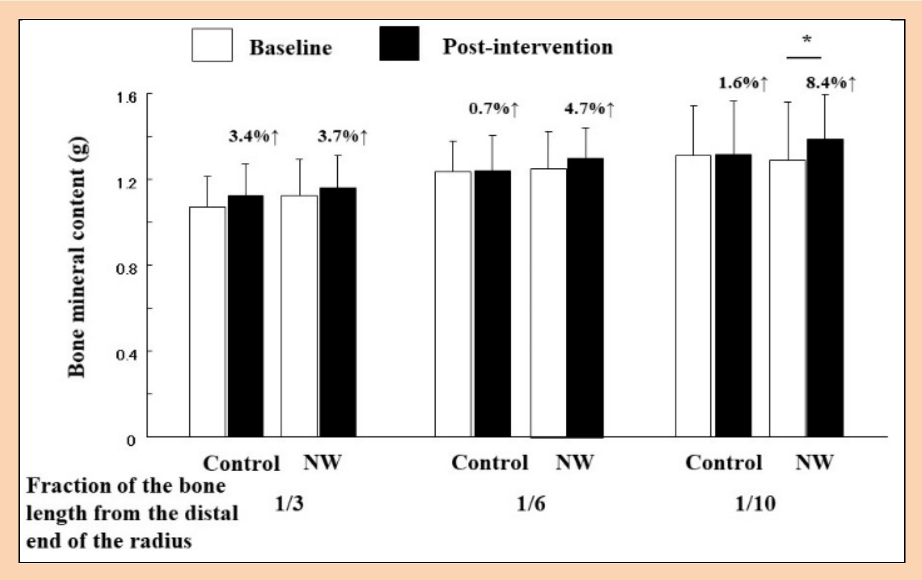

Figure 2. **Bone mineral content 1/3, 1/6, and 1/10 of the bone length from the distal end of the radius at baseline and post-intervention.** * $p < 0.05$.

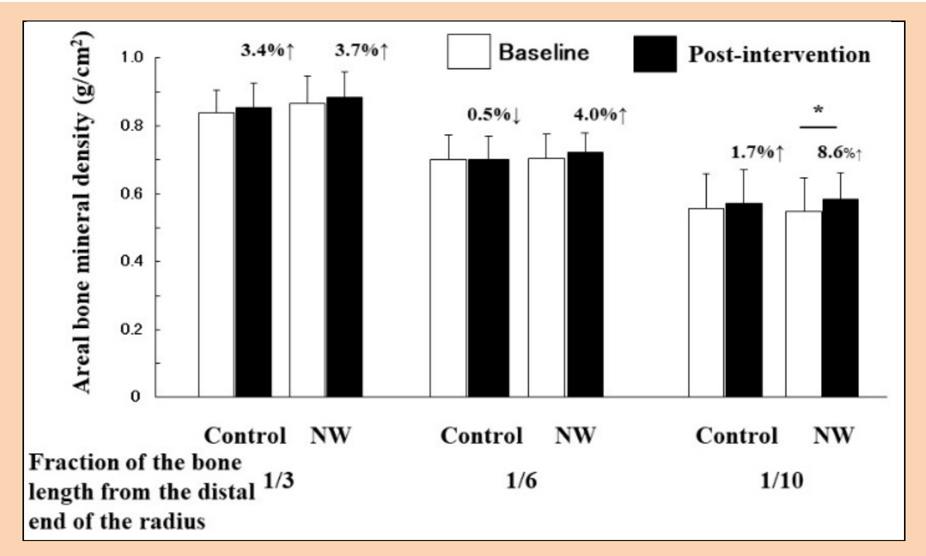

Figure 3. **Areal bone mineral density (aBMD; g/cm^2) at baseline and post-intervention.**

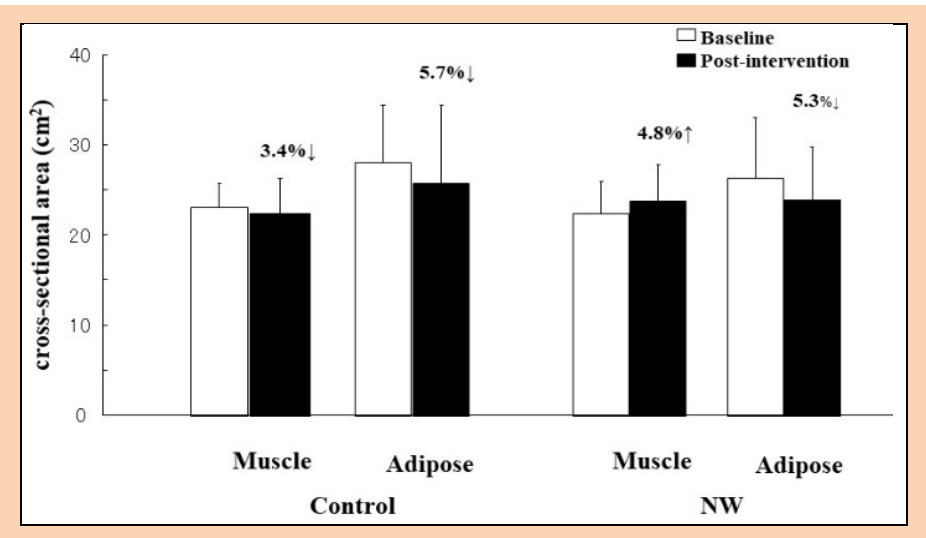

Figure 4. **Muscle and adipose cross-sectional area (CSA) at the mid-humeral level at baseline and post-intervention.**

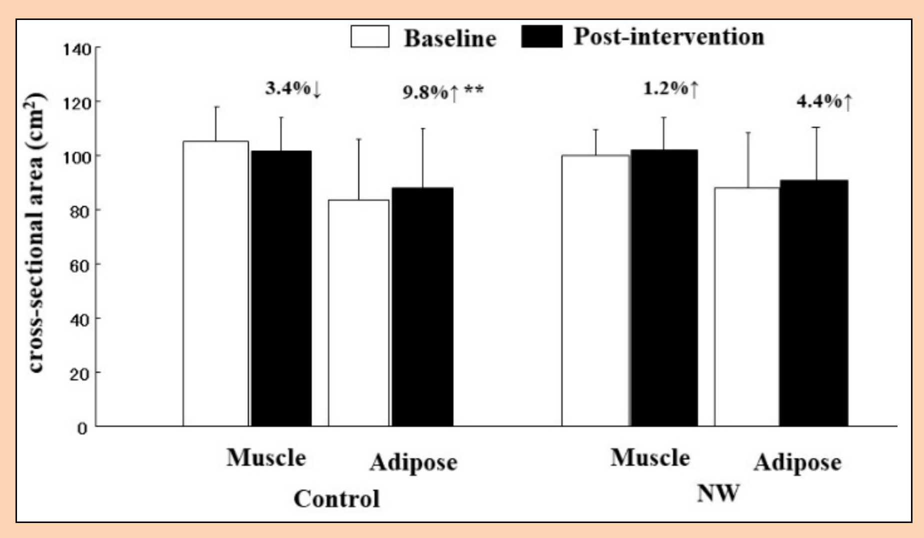

Figure 5. Muscle and adipose cross-sectional area (CSA) at the mid-femoral level at baseline and post-intervention.

Discussion

The most important finding of this study was that the BMC and aBMD 1/10 of the bone length from the distal end of the radius improved in premenopausal young women after a NW intervention consisting of at least 30 min of NW training three times a week for 6 months. The NW pole push-off movements may create more stress in the ultra-distal radius (1/10) than closer to the midpoint of the radius (1/3 or 1/6 of the bone length from the distal end of the radius).

Repetitive high-impact (Bass et al, 2002; Kontulainen et al., 2002) and weight-bearing (Proctor et al., 2002) loading on the upper limbs, such as during tennis, squash and gymnastics, enhances upper limb bone mass (racket sports) and increases BMC and BMD (cross-sectional study of gymnasts). Upper body resistance exercise increases forearm bone mass (Babatunde et al., 2019). In addition, resistance training, such as 12 machine and dumbbell exercises and a medicine ball toss-and-catch against a wall exercise, is effective at preventing distal radial bone loss (Duff et al., 2017) and impact exercise of the forearm involving the arrest of falls against a wall prevented distal radial bone loss (Greenway et al., 2015).

Gravitational mechanical stress is an effective stimulator of the osteogenic response. In a study by Khort *et al.* (1997), the forces produced by the muscles during resistance exercise were transmitted to the skeleton, but did not have positive effects on the femoral neck; however, the ground reaction force-type of movement significantly increased femoral neck strength. High-impact exercise increases BMD at the corresponding site without any effects on muscle strength and muscle mass (Kohrt et al., 2009). Essentially, gravitational high-impact loading is an effective osteogenic stimulus and efficiently enhances bone strength. For example, only five jumps per day (Umemura et al., 1997) were required to improve the strength of regional bones in immature rats. Similarly, in humans, only 10 daily vertical jumps three times a week were sufficient to increase BMC and aBMD in the femoral neck in premenopausal young women (Kato et al., 2006).

The upper limbs do not receive a gravitational compression load from reaction forces transmitted from the ground during daily activities (Kohrt et al., 2009). However, the NW pole push-off movement generates a ground reaction force and transmits it to the hands and distal radius through the NW pole grip and strap. It should be noted that the level of strain likely exceeded that generated during routine physical activity. This transmission of ground reaction forces through the NW poles is an unusual stimulus for the non-weight-bearing radius.

A three-dimensional finite element model has previously been used to simulate impact forces on the distal radius and to predict fractures (Bhatia et al., 2015). This study concluded that off-axis loads caused failure of the distal radius at lower magnitudes than axial loads. This means that if a mechanical stress is applied on a vector deviating from the long axis direction of the radius, it is more effective than if the same stress is applied in the long-axis direction. The present study has shown that during NW, the pole push-off movements on the ground provide an off-axis load to the distal radius and may be an effective osteogenic stimulus, especially in the ultra-distal radius, despite the magnitude of the individual loads being relatively low. At the distal end of radius, there is no bone marrow cavity and the percentage of trabecular bone is higher than at the sites 1/3 and 1/6 of the bone length from the distal end of the radius. It is known that greater responses to mechanical stress occur in trabecular bones than in cortical bones (Lang et al., 2006).

This study had some limitations. First, we could not measure the magnitude of the stress 1/10, 1/6 and 1/3 of the bone length from the distal end of the radius at the moment of NW pole push-off. In our study, the BMC and aBMD increased significantly only at 1/10 of the bone length from the distal end of the radius, which may have been the result of a greater osteogenic response to the compression load transmitted from the ground. Although the values do not describe the site-specific strain at the ultra-distal radius, Schiffer et al. (2009) reported that the mean axial forces measured by built-in strain gauges in NW poles being used on a concrete surface were 0.06- and 0.10-times body weight. Bhatia et al. (2015) showed that a higher compressive strain was present at the periosteal surface of the ultra-distal radius than at the midpoint of the radius, using participant-specific finite element models. In the present study, a significant increase in BMC was observed at 1/10 of the bone length from the distal radius, where the mechanical stress deviated from the longitudinal direction of the radius. Jumping training has also been widely used as a high-impact weight-bearing exercise to strengthen the lumbar spine and proximal femur in animals (Umemura et al., 1997; Honda et al., 2008) young women (Kato et al., 2006) and older women (Snow et al., 2000). The effective peak ground reaction force during the jumping training was 4.76-times body weight in the young women (Kato et al., 2006), but 0.49-times body weight has been shown to be effective at promoting osteogenesis at the distal end of radius during a dynamic loading exercise program (Wang and Salam, 2004).

A major strategy for the prevention of osteoporosis is the development of the peak bone mass accrual by the late 20's (Kohrt et al., 2004). High-impact and weight-bearing exercises during childhood (Johannsen et al., 2003; McKay et al., 2005) and adulthood (Bassey and Ramsdale, 1994; Kato et al., 2015) have been reported to assist with peak bone mass accrual and to have long-lasting benefits on bone in later life, even after the age of 50 (Kato et al., 2009). NW exercise may also represent a useful osteogenic exercise for the improvement of peak bone mass in younger adults.

Although the change was not statistically significant, the muscle CSA at the mid-femoral level decreased by a mean 3.4% and the adipose CSA significantly increased (9.8%) in the Control group during the 6 months of the study. In contrast, the muscle CSA increased by a mean 1.2% and the increase in adipose CSA was also smaller than that of the control group (9.8% *vs*. 4.4%) (Figure 5). Although these differences were not statistically significant, 6 months of NW training may at least maintain muscle CSA in the upper and lower extremities. Therefore, NW may reduce fracture risk in older adults.

Conclusion

In conclusion, we have shown that 6 months of NW training increases BMC and aBMD at 1/10 of the bone length from the distal end of the radius, without causing a significant increase in muscle CSA at the mid-humeral level. BMC and aBMD were increased in non-weight-bearing bone by using gravitational mechanical loading generated by relatively weak stimuli, compared with that required for a weight-bearing bone, such as the femur. Ground reaction forces, including from the NW pole push movement against the ground, are effective at increasing the strength of non-weight-bearing bone and although the load stimulus used in this study was relatively weak, the strain likely exceeded that generated during routine daily activities.

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Key points

- Ultra-distal radius BMC and aBMD was increased without any significant increase in corresponding muscle CSA.
- BMC and aBMD were enhanced in non-weight-bearing bone by using gravitational mechanical loading generated by relatively low stimuli.
- NW pole push movement against the ground was effective for increasing the strength of non-weight-bearing bone.

AUTHOR BIOGRAPHY

Takeru KATO
Employment
Professor of Asahi University, Department of Health Science and Sports Sciences, School of Health Sciences, Mizuho, Gifu, Japan
Degree
Ph.D.
Research interests
Exercise physiology, Exercise and bone, Sports biomechanics, Under water exercise,
E-mail: t-kato@alice.asahi-u.ac.jp

Toru TOMIOKA
Employment
Professor of Meijo University, Faculty of Foreign Studies, Nagoya, Aichi, Japan
Degree
Ph.D.
Research interests
Exercise physiology, Nordic Walking,
E-mail: tomioka@meijo-u.ac.jp

Takenori YAMASHITA
Employment
Suzuka University of Medical Science, Faculty of Health Sciences, Department of Clinical Radiation, Suzuka, Mie, Japan
Degree
Ph.D.
Research interests
Clinical radiation, Medical image processing and analysis,
E-mail: takenori@suzuka-u.ac.jp

Hidehiro YAMAMOTO
Employment
Asahi University, Department of Health Science and Sports Sciences, School of Health Sciences, Mizuho, Gifu, Japan
Degree
MSc.
Research interests
Sports biomechanics, Golf swing analysis,
E-mail: yamamoto@alice.asahi-u.ac.jp

Yasuhiro SUGAJIMA
Employment
Professor of Asahi University, Department of Health Science and Sports Sciences, School of Health Sciences, Mizuho, Gifu, Japan
Degree
Ph.D.
Research interests
Neurophysiology, EMG activity under the micro gravity environment, Exercise physiology,
E-mail: ysugajima@alice.asahi-u.ac.jp

Norikazu OHNISHI
Employment
Professor of Mie Prefectural College of Nursing, Faculty of Nursing, Tsu, Mie, Japan
Degree
Ph.D.
Research interests
Body temperature regulation, Exercise physiology,
E-mail: norikazu.oonishi@mcn.ac.jp

✉ **Takeru Kato**
Asahi University, Department of Health Science and Sports Sciences, School of Health Sciences, Mizuho, Gifu, Japan