https://doi.org/10.5817/StS2024-1-18

Rest Pauses Between Strength Training Series and Changes In Bone Density in Athletes – A Pilot Study

Jan Caha[1], Petr Babula[2], Jan Cacek[1], Marián Vanderka[1]

[1]*Faculty of Sport Education, Masaryk university, Brno, Czech Republic*

[2]*Faculty of Medicine, Masaryk university, Brno, Czech Republic*

ABSTRACT

A bone mineral density (BMD) test can provide a snapshot of bone health. The test identifies osteoporosis, determines the risk of fracture (broken bones), and measures the response to osteoporosis treatment. The study attempted to determine the effects of three different rest periods (30, 60, 120 sec.) as a variable factor in strength training on selected indicators of total bone density. The experiment involved four groups of five participants: three experimental groups and one control group. The study's participants were characterized as athletic in ability, with strength sufficient training experience of more than 3 years and technical knowledge; the participants were male, aged 18-35 years (n = 20). To evaluate the effect of rest pauses in strength training on bone density, the states before and after the experiment were compared in individuals, the experimental groups and the control group. For analysis we use the BMD index (g /cm2), T-score, and Z-score. In the group which applied the 30-second rest period, the mean BMD increase was 0.0046 g/cm2 with a standard deviation of 0.0079 g/cm2, in the 60-second group it was -0.0260 g/cm2 with a standard deviation of 0.0412 g/cm2, and in the 120-second group it was 0.0082 g/cm2 with a standard deviation of 0.0168 g/cm2. At a statistical significance level of 5%, no significant difference in bone density was found between the groups for different rest pauses, but the factual significance of the relationship of strength training as a possible prevention of osteoporosis and solving problems of the musculoskeletal system.

Keywords: bone density; strength; strength training; muscle mass; hypertrophy

INTRODUCTION

Bone density, osteoporosis and strength training

The effect of strength training on bone density is demonstrable. Several studies prove the benefits of strength training in adults and seniors. Research shows that muscle loss (sarcopenia) is linked to bone loss (osteopenia) [1], [[2], [3]. Osteoporosis is currently estimated to affect 7–10% of the population. In Czechia, its incidence is as high as 1,000,000 people. Osteoporosis affects one in three women and one in five men over the age of 50. At the age of 70, it affects one in two women [4]. Other important risk factors include (in addition to ageing and endocrine changes) obesity and possibly associated type 2 diabetes mellitus. Metabolic complications contribute significantly to altered bone homeostasis, which in turn leads to an increased risk of osteoporosis-related fractures [5].

Adults who do not perform any resistance training may experience a 1–3% decrease in bone mineral density (BMD) every year. So, it seems logical that strength training, which promotes gains in muscle mass is also expected to increase BMD, and most studies support this observation. Several longitudinal studies show significant increases in BMD after 4 to 24 months of strength training [1], [2], [3]. A number of smaller studies were summarised in the systematic review by Haque et al., 2024, with the conclusions that high velocity resistance training plays a role in increasing BMD of the lumbar spine, femoral neck, and total hip [6]. However, the authors of the publication point to the considerable methodological inconsistency of the individual studies and therefore the absence of meta-analyses. In addition, the effect of strenght training on BMD can be influenced by a number of dietary supplements, such as L-carnitine [7]. However, most studies in this area support the conclusion that resistance training has a positive association with high BMD in both younger and older adults and may have a stronger effect on bone density than other types of exercise training, including aerobic exercise [8], [9], [10], [11], [12], [13], [14]. Although much of the research on strength training and bone density has been conducted on older women, the evidence shows that young men can increase BMD by 2.7–7.7% through resistance training. The extent of change in BMD relates to different responses in bone mass since the musculoskeletal effects of resistance training are relatively site-specific [15], [16], [17].

Pauses between series and strength training

Rest breaks between work sets are a basic training variable which significantly alters the total training time and regeneration and supply of energy substrates for the next work set. It affects metabolic stress and the subsequent length and ability to deliver maximum performance. Acute and delayed biochemical, haematological and neuromuscular responses to the Rest-pause (RP) method and traditional resistance training (TRT) after 48 h were described in de Azevedo et al, 2021. The work showed that only creatine kinase, aspartate aminotransferase, neutrophils and white blood cells increased after the protocols ($p < 0.05$) and returned to baseline values after 48 h [18]. In many experimental studies, the rest breaks typically ranged from 30 to 300 seconds, broken down into short rest periods (up to 30 sec.), medium rest periods (up to 60 sec.) and long rest periods (180–300 sec.) [19]. It has been shown that short rest breaks (30 s) generate high metabolic stress, but do not provide enough rest for subsequent maximum strength performance. However, they are believed to be effective in building muscle mass, but less so for building strength [20], [21]. Medium breaks are a compromise between short and long breaks and provide sufficient time to regenerate the energy stores used in repetitive effort training and cause high metabolic stress. They are also indicated in the case of high hypoxia and subsequently may have a more significant impact on muscle mass, but also through a higher hormonal 'peak' in response to strength training. Long rest breaks (over 180 sec.) benefit maximum strength regeneration between sets and thus maximize the possible mechanical tension and exertion of greater loads (for example, during maximum strength training). Metabolic stress in this case is not as high as with short or moderate rest breaks [22], [23], [24], [25].

Although the relationship between strength training and bone density is described in several studies, much of the research does not provide any detailed comparison of rest periods and their effect on BMD. The definition of intensity is often cited as a training variable, but sufficient comparisons are lacking. The current study's main area of interest is whether the length of rest breaks during strength training produces any difference in the change in bone density, and whether a relationship exists between strength training, rest break period and bone density. This investigation is potentially useful because bone density is a major factor in preventing injury in athletes as well as in general population and may help to to predict and prevent risk of osteoporosis.

When examining the relationship between strength training and BMD, we encounter different durations of intervention programs. Some studies work with significant changes in bone density and duration of intervention in the order of weeks [26], [27], [28]. The duration of intervention in these cases is 6-12 weeks. But also studies in which the effect of strength training is monitored in the order of months [29] and years [30]. Shorter intervention times usually occur in young and middle-aged athletes. However, the literature does not agree on the optimal duration of a training intervention. According to the available literature, the DXA analytical instrument used is able to record changes even over a period of days with good reproducibility of the results [31].

In the available literature, we are not able to find an analysis of the relationship between rest breaks in strength training and bone density. However, the length of recovery affects the intensity of the procedure. We know that there is a relationship between exercise intensity and bone density. This is descRIBED IN HIS META-ANALYSIS BY KISTLER-FISCHBACHER, M., WEEKS, B., & BECK, B. [26].

METHODS

Participants and experimental protocol

The participants were 20 males aged 18–35 years (n = 20), divided into four groups of 5, three groups for the experiment and one group as a control. Each participant had more than five years of training experience and was trained in proper exercise technique; they can be considered experienced athletes. All participants had been free of any lower-body, musculoskeletal or neuromuscular injuries in the previous six months, and all participants claimed no current or previous use of any anabolic steroids. The average participant age was 25.7 years; average weight before the experiment was 85.6 kg; average height was 182 cm. During the experiment, the participants did not engage in any other activities that could significantly alter the results of the study. The participants were instructed to follow a prescribed nutritional plan to consume 2 grams of protein per kilogram of body weight per day and no intake of dietary supplements that would have a significant effect on sports performance. All participants were advised to maintain a balanced energy intake and a typical diet consisting of 40–50% carbohydrates. The plan was designed to maintain energy levels. Before visiting the laboratory, the participants were instructed in further aspects of dietary behaviour, which included the omission of alcohol and stimulants such as nicotine. Each participant visited the laboratory on two occasions separated by five weeks. On the first visit, the participant was assessed for body composition and bone density according to BMD, Z-score and T-score.

Resistance exercise protocol

The participants were given a training plan and instructed on the individual exercise techniques. Any individual discrepancies in exercise techniques were standardized. All participants followed an identical training protocol (Annex 1) for five weeks. The experimental variable was difference in the length of rest breaks between training sets (30, 60, 120 sec.). Details of training protocol are shown in Annex 1.

The protocol of training with different pauses allows to determine whether primarily metabolic stress (not providing enough rest for subsequent maximal strength performance and its associated potential for efficient muscle mass building, but less so for strength building) or high mechanical stress (benefiting strength recovery between sets and maximizing the development of higher loads) is related to changes in BMD.

METHODS USED

A bone mineral density (BMD) test

A bone mineral density (BMD) test measures how much calcium and other minerals are in the bones and bone structures. The DEXA method mainly measures the lumbar spine and the proximal femur of the lower limb. The examination takes less than 4 minutes and the radiation dose is very low. The attenuated X-rays are directly proportional to the mineral content of the tissue after passing through the bone. The amount of bone mineral is expressed in g/cm3. Compared to other imaging methods, DEXA has a low radiation burden and high examination speed. This test helps detect osteoporosis and predict the risk of bone fractures or other injuries. The BMD test measures bone mineral density and compares it to an established standard to allocate a score. Although no bone density test is 100% accurate, the BMD test is an important predictor of whether a person might suffer a fracture or bone disease in the future [33].

The T-score

A T-score was obtaioned as a difference between bone mineral density measured in a participant and 0, which is the bone mineral density of a healthy young adult. It is commonly used in medicine to evaluate risk of osteoporosis. The differences between a subject's BMD and the average of a healthy young adult are measured in units called standard deviations (SD). A score of 0 means that BMD is equal to the average for a healthy young adult. The more standard deviations below 0, denoted as negative numbers, the lower the BMD and the higher the risk of fracture [26, 34]. In the study, the T-score between +1 and −1 was considered normal or healthy. A T-score between −1 and −2.5 indicated a low bone mass, although not low enough for a diagnosis of osteoporosis. The T-score of −2.5 or lower indicated osteoporosis; the greater the negative number, the more severe the osteoporosis [33]. This classification is also based on the WHO classification.

T-score = (Subject BMD - Average BMD) / Standard Deviation of the average BMD [26].

The Z-score

Z-score was used as another possible determinant of BMD assessment. A normal BMD Z-score ranges from −2.5 to 2.5. A normal Z-score indicates a BMD similar to other healthy people in the same age group. A lower Z-score indicates a lower BMD; a higher Z-score indicates a higher BMD [33].

Z-score = (Subject BMD - Average BMD of subject age group) / Standard Deviation of the average BMD of subject age group [33].

DEXA measurements

Dual energy X-ray absorption spectrometry (DEXA) produces high accuracy in body composition analysis. The participants in the current study were measured for body composition (FFM – fat free mass, fat, muscle mass, bone density) using a DEXA machine - Hologic type (TBAR1209 - NHANES BCA calibration). The values measured on the first visit, i.e., body composition and bone density, were re-examined on the second visit, also on a DEXA device.

PROCEDURES

Statistical evaluation

Using analysis of variance (ANOVA), the study compared the BMD in the three experimental groups according to length of rest (30, 60, 120 sec.). The Shapiro–Wilk test was applied to verify the assumption of data normality, and the Leven test was used to check the assumption of homogeneity of variance. Because the difference in BMD was zero in the control group before and after the experiment, the effect of the experiment was tested on each experimental group using a one-sample t-test against the constant 0. Comparison of the effect of the experiment between individual groups was performed using ANOVA. The selected level of significance was 0.05, and calculations were performed in the TIBCO STATISTICA 13 software (TIBCO Software Inc., USA). Descriptive statistics were calculated for each variable: mean, standard deviation, median, minimum, and maximum. These are presented in tables and box plots.

RESULTS

The participant pool, together with the methodology used, was intended to provide answers to the following questions and hypotheses: i. How do mean bone density values change as a result of strength training?, ii. Are there any significant differences between the experimental groups in bone density change? And iii. Which rest period resulted in the greatest increase in bone density?

BMD

This section describes the results from the five-week training programme. At a statistical significance level of 5%, no significant difference in BMD was observed. A comparison of the effect of the experiment, measured as the difference in BMD values before and after the experiment, with the zero value, indicated no statistically significant difference in any group ($p > 0.05$). Negative effect was observed in the group which applied 60-second rest periods. Table 1 summarizes the changes in body composition as processed by the one-sample t-test, Table 2 shows corresponding descriptive statistics.

Table 1. Changes in body composition

One-sample t-test				
Group	mean	standard deviation	tested value	*p*-value
30 sec (n=5)	0.0046	0.0079	0	0.264
60 sec (n=5)	-0.0260	0.0412	0	0.231
120 sec (n=5)	0.0082	0.0168	0	0.335

Table 2. Descriptive statistics

Variable	Group	N	Mean	St. Dev.	Median	Min	Max
BMD before	**control**	5	1.19	0.07	1.21	1.07	1.25
	30	5	1.24	0.05	1.23	1.18	1.30
	60	5	1.23	0.02	1.23	1.20	1.26
	120	5	1.17	0.13	1.11	1.06	1.36
BMD after	**control**	5	1.19	0.07	1.21	1.07	1.25
	30	5	1.21	0.07	1.22	1.12	1.29
	60	5	1.24	0.03	1.23	1.21	1.26
	120	5	1.17	0.13	1.13	1.05	1.35
Difference BMD	**control**	5	0.0000	0.0000	0.0000	0.0000	0.0000
	30	5	-0.0260	0.0412	-0.0150	-0.0970	0.0080
	60	5	0.0046	0.0079	0.0060	-0.0040	0.0140
	120	5	0.0082	0.0168	0.0070	-0.0070	0.0340
Age	**control**	5	24.60	2.30	25.00	21.00	27.00
	30	5	23.40	3.85	22.00	20.00	28.00
	60	5	29.60	6.69	30.00	22.00	38.00
	120	5	25.20	5.89	27.00	18.00	31.00
Height	**control**	5	184.80	2.28	185.00	182.00	187.00
	30	5	181.20	5.17	182.00	173.00	186.00
	60	5	182.60	3.71	182.00	178.00	188.00
	120	5	180.40	5.81	179.00	175.00	187.00
Weight before	**control**	5	93.00	14.44	93.00	75.00	115.00
	30	5	84.20	7.60	87.00	71.00	90.00
	60	5	84.00	2.45	83.00	81.00	87.00
	120	5	81.20	6.87	80.00	75.00	91.00
Weight after	**control**	5	93.20	14.38	94.00	76.00	115.00
	30	5	85.40	7.73	88.00	72.00	91.00
	60	5	82.80	3.11	83.00	78.00	86.00
	120	5	82.60	6.54	80.00	76.00	91.00

In the group which applied the 30-second rest period, the mean BMD increase was 0.0046 g/cm2 with a standard deviation of 0.0079 g/cm2, in the 60-second group it was -0.0260 g/cm2 with a standard deviation of 0.0412 g/cm2, and in the 120-second group it was 0.0082 g/cm2 with a standard deviation of 0.0168 g/cm2.

ANOVA resulted in *p*-values with three decimal places at 0.116, i.e., greater than 0.05. Therefore, the null hypothesis was not rejected. At a significance level of 0.05, no difference in the mean values of BMD increase was observed in the three groups according to the rest period (30, 60, 120 sec.). Figure 1 plots the mean ± standard deviation, minimum and maximum range. You can find it in Figure 1. (Difference in BMD)

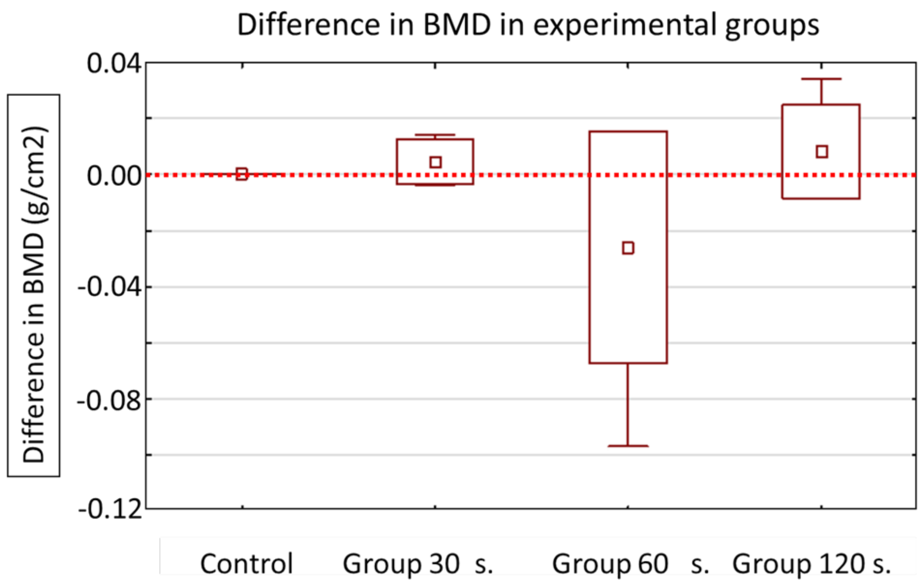

Figure 1. Difference in BMD.

The z-score and t-score indicate a comparison of the sample to the population standard. Most of the participants showed higher or the same bone hardness as the population average; no reduction in bone hardness appeared.

DISCUSSION

The aim of the study was to determine which of the tested rest times during strength training produced the most significant effect on bone density. Even though the findings revealed no significant differences in bone density change between groups, the effect of strength training on bone density, however, was verified. Interestingly, this effect was both positive and negative. The intermediate rest period group showed a loss of bone density. Unfortunately, we do not have an explanation for the loss of bone density from the available literature, so this effect would require further investigation. Both the short and long rest period groups experienced an increase in bone density. A comparison of these data with changes in body weight indicates a similarity in changes between weight and bone density. Changes in body weight can also be linked to energy availability, an observation which is linked to bone density in the literature. But how can this type of training affect BMD? By what mechanisms? Muscle, like adipose tissue, is endocrinally active, and produces a variety of hormones, together called myokines. Myokines serve as signaling and integrative molecules that integrate muscle tissue with a variety of other tissues and organs. Myokines serve as signaling and integrative molecules that integrate muscle tissue with a variety of other tissues and organs. The most important myokine-mediated communication axes include muscle tissue-fat tissue (and hence energy metabolism), muscle tissue-CNS (including regulation of food intake), or muscle tissue-GIT-endocrine pancreas (insulin and its anbabolic effect). Currently, more than 650 different myokines are known [41]. However, the functional interconnection between muscle and bone tissue has been described. Myokines are widely involved in bone metabolism, influencing bone resorption and formation by interacting with factors related to bone cell secretion or influencing bone metabolic pathways [35]. A study by Kumar et al., 2023 shows that biomechanical stimulation of muscle tissue leads to the secretion of myokines, which in turn affect the architecture of bone tissue [36]. One of the myokines, irisin, increases bone formation and, conversely, inhibits bone resorption, in postmenopausal women [37]. These findings were based on several previous studies [38]. The outcome of the pilot study may also be influenced by genetic predispositions related to strength training and bone density, such as the α-actinin-3 R577X polymorphism mentioned in the 2022 study. [42] The pilot study presented here is original in that it examines the effect of strength training, namely the length of rest breaks between training sets, on BMD. A study of this type has not been conducted before. Moreover, the set of participants, experienced athletes, is also very original. The pilot study provides the first results of this type, however, it is clear that it will be complemented in the direction of studying metabolic and endocrine changes with respect to non-significant myokines. Although several studies have been published on the relationship between strength training and increased myokine production [39, 40],the importance of rest breaks has not yet been clarified. There is therefore sufficient opportunity for further research.

CONCLUSION

Addressing the research questions, no significant differences in bone density change were observed. However, the effect of strength training on bone density and body weight was evident.

Answers to research questions and hypothese are as follows:

RQ1: How do mean bone density values change as a result of strength training?

Positively in two groups, negatively in one group.

RQ2: Are there any significant differences between the experimental groups in bone density change?

No significant differences.

RQ3: Which rest period resulted in the greatest increase in bone density?

Group with the long rest period of 120 seconds.

The small sample size is the main drawback to the study and may have resulted in an error. Low energy availability in one group was also a problem, and the short duration of the experiment may was limitation to reveal any significant differences.

The practical application of the findings will help in establishing more effective training programmes which incorporate appropriate rest times required for maintaining bone density and preventing the onset of osteoporosis. Although it cannot be proven that one rest period is more suitable than another, it can be stated that strength training is essential to preventing osteoporosis and has a positive effect on bone density. Strength training should be a regular part of every person's sports regime. Weight management and greater FFM and energy sufficiency can also be monitored as crucial factors in bone health.

REFERENCES

Aloia, J. F., McGowan, D. M., Vaswani, A. N., Ross, P., & Cohn, S. H. (1991). Relationship of menopause to skeletal and muscle mass. *American Journal of Clinical Nutrition, 53*(5), 1378–1383.

Bevier, W. C., Wiswell, R. A., Pyka, G., Kozak, K. C., Newhall, K. M., & Marcus, R. (1989). Relationship of body composition, muscle strength, and aerobic capacity to bone mineral density in older men and women. *Journal of Bone and Mineral Research, 4*(3), 421–432.

Hurley, B. (1995). Strength training in the elderly to enhance health status. *Medicine, Exercise, Nutrition & Health, 4*, 217–229.

20. říjen - Světový den osteoporózy [online]. (2021, 20.10.2021). Retrieved July 31, 2022, from http://www.szu.cz/publikace/mezinarodni-den-osteoporozy

Ali, D., Tencerova, M., Figeac, F., Kassem, M., & Jafari, A. (2022). The pathophysiology of osteoporosis in obesity and type 2 diabetes in aging women and men: The mechanisms and roles of increased bone marrow adiposity. *Frontiers in Endocrinology, 13*, 981487. https://doi.org/10.3389/fendo.2022.981487

Haque, I., Schlacht, T. Z., & Skelton, D. A. (2023). The effects of high velocity resistance training on bone mineral density in older adults: A systematic review. *Bone, 179*, 116986. https://doi.org/10.1016/j.bone.

Olek, R. A., Samborowska, E., Wisniewski, P., Wojtkiewicz, P., Wochna, K., & Zielinski, J. (2023). Effect of a 3-month L-carnitine supplementation and resistance training program on circulating markers and bone mineral density in postmenopausal women: a randomized controlled trial. *Nutrition & Metabolism, 20*(1), 32. https://doi.org/10.1186/s12986-023-00752-1

Cussler, E. C., Lohman, T. G., Going, S. B., Houtkooper, L. B., Metcalfe, L. L., Flint-Wagner, H. G., Harris, R. B., & Teixeira, P. J. (2003). Weight lifted in strength training predicts bone change in postmenopausal women. *Medicine and Science in Sports and Exercise, 35*(1), 10–17.

Dornemann, T., McMurray, R., Renner, J., & Anderson, J. (1997). Effects of high intensity resistance exercise on bone mineral density and muscle strength of 40-50 year-old women. *Journal of Sports Medicine and Physical Fitness, 246–251.*

Going, S., Lohman, T., Houtkooper, L., Metcalfe, L., Flint-Wagner, H., Blew, R., Stanford, V., Cussler, E., Martin, J., Teixeira, P., Harris, M., Milliken, L., Figueroa-Galvez, A., & Weber, J. (2003). Effects of exercise on bone mineral density in calcium-replete postmenopausal women with and without hormone replacement therapy. *Osteoporosis International, 14*(8), 637–643. https://doi.org/10.1007/s00198-003-1436-x

Nelson, M. E., Fiatarone, M. A., Morganti, C. M., Trice, I., Greenberg, R. A., & Evans, W. J. (1994). Effects of high-intensity strength training on multiple risk factors for osteoporotic fractures. A randomized controlled trial. *JAMA, 272*(24), 1909–1914. https://doi.org/10.1001/jama.1994.03520240037038

Nickols-Richardson, S. M., Miller, L. E., Wootten, D. F., Ramp, W. K., & Herbert, W. G. (2007). Concentric and eccentric isokinetic resistance training similarly increases muscular strength, fat-free soft tissue mass, and specific bone mineral measurements in young women. *Osteoporosis International, 18*(6), 789–796. https://doi.org/10.1007/s00198-006-0305-9

Von Stengel, S., Kemmler, W., Kalender, W. A., Engelke, K., & Lauber, D. (2007). Differential effects of strength versus power training on bone mineral density in postmenopausal women: a 2-year longitudinal study. *British Journal* *of Sports Medicine, 41*(10), 649–655. https://doi.org/10.1136/bjsm.2006.033480

Yarasheski, K., Campbell, J., & Kohrt, W. (1997). Effect of resistance exercise and growth hormone on bone density in older men. *Clinical Endocrinology, 223–229*.

Almstedt, H. C., Canepa, J. A., Ramirez, D. A., & Shoepe, T. C. (2011). Changes in bone mineral density in response to 24 weeks of resistance training in college-age men and women. *Journal of Strength and Conditioning Research, 1098–1103*.

Kerr, D., Morton, A., Dick, I., & Prince, R. (1996). Exercise effects on bone mass in post-menopausal women are site-specific and load-dependent. *Journal of Bone and Mineral Research, 218–225*.

Layne, J., & Nelson, M. (1999). The effects of progressive resistance training on bone density: a review. *Medicine and Science in Sports and Exercise, 25–30*.

Calandrini de Azevedo, A. B., Penna, E. M., Costa, A. S. L., Filho, A. J. M., Franco, E. C. S., & Coswig, V. S. (2021). Acute and delayed biochemical, hematological, and neuromuscular responses to the Rest-pause resistance training method. *Fatigue: Biomedicine, Health & Behavior, 9*(2), 99-112., https://doi.org/10.1080/21641846.2021.1942949

Willardson, J. M. (2006). A brief review: Factors affecting the length of the rest interval between resistance exercise sets. *Journal of Strength and Conditioning Research, 20*, 978-984.

Goto, K., Ishii, N., Kizuka, T., & Takamatsu, K. (2005). The impact of metabolic stress on hormonal responses and muscular adaptations. *Medicine & Science in Sports & Exercise, 37*, 955-963.

Miranda, H., Fleck, S. J., Simão, R., Barreto, A. C., Dantas, E. H., & Novaes, J. (2007). Effect of two different rest period lengths on the number of repetitions performed during resistance training. *Journal of Strength and Conditioning Research, 21*, 1032-1036.

Kraemer, W. J., Marchitelli, L., Gordon, S. E., Harman, E., Dziados, J. E., Mello, R., Frykman, P., McCurry, D., & Fleck, S. J. (1999). Hormonal and growth factor responses to heavy resistance exercise protocols. *Journal of Applied Physiology, 69*, 1442-1450.

Kraemer, W. J., Gordon, S. E., Fleck, S. J., Marchitelli, L. J., Mello, R., Dziados, J. E., Friedl, K., Harman, E., Maresh, C., & Fry, A. C. (1991). Endogenous anabolic hormonal and growth factor responses to heavy resistance exercise in males and females. *International Journal of Sports Medicine, 12*, 228-235.

Willardson, J. M. (2006). A brief review: Factors affecting the length of the rest interval between resistance exercise sets. *Journal of Strength and Conditioning Research, 20*, 978-984.

Kraemer, W. J., Noble, B. J., Clark, M. J., & Culver, B. W. (1987). Physiologic responses to heavy-resistance exercise with very short rest periods. *International Journal of Sports Medicine, 8*, 247-252.

Izard, R. M., Fraser, W. D., Negus, C., Sale, C., & Greeves, J. P. (2016). Increased density and periosteal expansion of the tibia in young adult men following short-term arduous training. *Bone, 88*, 13-19.

Joo, W., Singh, H., Ahles, C. P., Lee, Y., Colazas, W., Lee, L. C., Prakash, A., Jaque, S. V., & Sumida, K. D. (2015). Training-induced increase in bone mineral density between growing male and female rats. *International Journal of Sports Medicine, 992-998*.

Mosti, M. P., Carlsen, T., Aas, E., Hoff, J., Stunes, A. K., & Syversen, U. (2014). Maximal strength training improves bone mineral density and neuromuscular performance in young adult women. *Journal of Strength and Conditioning Research, 28*(10), 2935-2945.

Menkes, A., Mazel, S., Redmond, R., Koffler, K., Libanati, C., Gundberg, C., Zizic, T., Hagberg, J., Pratley, R., & Hurley, B. (1993). Strength training increases regional bone mineral density and bone remodeling in middle-aged and older men. *Journal of Applied Physiology, 74*(5), 2478-2484. https://doi.org/10.1152/JAPPL.1993.74.5.2478.

Lohman, T., Going, S., Hall, M., Ritenbaugh, C., Bare, L., Hill, A., Houtkooper, L., Aickin, M., Boyden, T., & Pamenter, R. (1995). Effects of resistance training on regional and total bone mineral density in premenopausal women: A randomized prospective study. *Journal of Bone and Mineral Research, 10*. https://doi.org/10.1002/JBMR.5650100705.

Lodder, M. C., Lems, W. F., Ader, H. J., Marthinsen, A. E., van Coeverden, S. C., Lips, P., Netelenbos, J. C., Dijkmans, B. A., & Roos, J. C. (2004). Reproducibility of bone mineral density measurement in daily practice. *Annals of the Rheumatic Diseases, 63*(3), 285–289. https://doi.org/10.1136/ard.2002.005678

Kistler-Fischbacher, M., Weeks, B., & Beck, B. (2021). The effect of exercise intensity on bone in postmenopausal women (part 2): A meta-analysis. *Bone, 143*, 115697. https://doi.org/10.1016/j.bone.2020.115697.

U.S. Food and Drug Administration. (2018). Bone Mass Measurement: What the Numbers Mean [online]. Retrieved July 31, 2022, from https://www.bones.nih.gov/health-info/bone/bone-health/bone-mass-measure

Severinsen, M. C. K., & Pedersen, B. K. (2021). Muscle-organ crosstalk: The emerging roles of myokines. *Endocrine Reviews, 41*(4), 594-609. https://doi.org/10.1210/endrev/bnaa016

Shao, M., Wang, Q., Lv, Q., Zhang, Y., Gao, G., & Lu, S. (2023). Advances in the research on myokine-driven regulation of bone metabolism. *Heliyon, 10*(1), e22547. https://doi.org/10.1016/j.heliyon.

Suresh Kumar, H., Barnett, E. N., Fowlkes, J. L., Kalaitzoglou, E., & Annamalai, R. T. (2023). Biomechanical stimulation of muscle constructs influences phenotype of bone constructs by modulating myokine secretion. *JBMR Plus*. https://doi.org/10.1002/jbm4.10804

Kornel, A., Den Hartogh, D. J., Klentrou, P., & Tsiani, E. (2021). Role of the myokine irisin on bone homeostasis: Review of the current evidence. *International Journal of Molecular Sciences, 22*(17), 9136. https://doi.org/10.3390/ijms22179136

Colaianni, G., Cuscito, C., Mongelli, T., Pignataro, P., Buccoliero, C., Liu, P., Lu, P., Sartini, L., Di Comite, M., Mori, G., Di Benedetto, A., Brunetti, G., Yuen, T., Sun, L., Reseland, J. E., Colucci, S., New, M. I., Zaidi, M., Cinti, S., & Grano, M. (2015). The myokine irisin increases cortical bone mass. *Proceedings of the National Academy of Sciences of the United States of America, 112*(39), 12157–12162. https://doi.org/10.1073/pnas.1516622112

Nam, J. S., Park, S. J., Ahn, C. W., Cho, E. S., Kim, H. J., & Kim, Y. (2024). Follistatin-like 1 is a myokine regulating lipid mobilization during endurance exercise and recovery. *Obesity, 352-362*. https://doi.org/10.1002/oby.23949

Tim-Yun Ong, M., Fu, S. C., Mok, S. W., Franco-Obregón, A., Lok-Sze Yam, S., & Shu-Hang Yung, P. (2022). Persistent quadriceps muscle atrophy after anterior cruciate ligament reconstruction is associated with alterations in exercise-induced myokine production. *Asia Pacific Journal of Sports Medicine, Arthroscopy, Rehabilitation and Technology*. https://doi.org/10.1016/j.asmart.2022.05.001

Johansson, H., Azizieh, F., Al Ali, N., Alessa, T., Harvey, N. C., McCloskey, E., & Kanis, J. A. (2017). FRAX- vs. T-score-based intervention thresholds for osteoporosis. *Osteoporosis International, 3099-3105*. https://doi.org/10.1007/s00198-017-4160-7\. PMID: 28782072; PMCID: PMC5881885.

Kobayashi, T., Seki, S., & Hwang, I. (2022). Relationship of muscle power and bone mineral density with the α-actinin-3 R577X polymorphism in Japanese female athletes from different sport types: An observational study. *Medicine, 101*(45), e31685. https://doi.org/10.1097/MD.0000000000031685

ANNEX 1

Training plan

- Training at 80% of 1RM (one repetition maximum)
- In the third week, increase to 85% of 1RM
- TUT (time under tension) = 3-0-1-0
- Rest period: 30, 60 or 120 seconds.
- Cardiovascular training is recommended as active regeneration after strength training

Weekly Schedule

- Mon – training set 1
- Tue – training set 2 – cardio activity 10 min
- Wed – free day
- Thu – training set 3
- Fri – training set 4
- Sat – training set 5 – cardio activity 10 min
- Sun – free day
- Repeat the cycle for subsequent weeks

Training Components

1. Warm up with 5–10 min of cardio activity
2. Joint mobilisation
3. Dynamic stretching and core activation
4. Main training programme

Training Set 1

Exercise	**Series**	**Repetition/weight (% 1RM)**
Dumbbell bench press	4*	7–8 (80 %)
Incline bench press	3*	7–8 (80 %)
Incline fly press	3	7–8 (80 %)
Pec deck	3	7–8 (80 %)
Cable fly	3	7–8 (80 %)
Dumbbell curl	4	7–8 (80 %)
Hammer curl	4	7–8 (80 %)

* before the main series, complete a series with 20% and 40% 1RM

Training Set 2

Exercise	**Series**	**Repetition/weight (% 1RM)**
Dumbbell shoulder press	4*	7–8 (80 %)
Machine shoulder press	3	7–8 (80 %)
Lateral raise	3	7–8 (80 %)
Frontal raise	3	7–8 (80 %)
Rope triceps pushdowns	4	7–8 (80 %)
Overhead triceps extension	4	7–8 (80 %)

* before the main series, complete a series with 20% and 40% 1RM

Training Set 3

Exercise	Series	Repetition/weight (% 1RM)
Back squat	4*	7–8 (80 %)
Leg press	3*	7–8 (80 %)
Quadricep extensions	3	7–8 (80 %)
Prone leg curl	3	7–8 (80 %)
Romanian deadlift	3	7–8 (80 %)
Standing calf raises	3	6–12 (80 %)

before the main series, complete a series with 20% and 40% 1RM

Training Set 4

Exercise	Series	Repetition/weight (% 1RM)
Lat pulldown	4*	7–8 (80 %)
Pull ups	3	7–8 (80 %)
Bent-over barbell rows	3	7–8 (80 %)
Seated cable rows	3	7–8 (80 %)
Cable pullover	4	7–8 (80 %)
Hyperextension	3	15

* before the main series, complete a series with 20% and 40% 1RM

Training Set 5

Exercise	Series	Repetition/weight (% 1RM)
Bicep curl	4*	7–8 (80 %)
Preacher curl	3	7–8 (80 %)
Triceps bench press	4*	7–8 (80 %)
Triceps dips	3	7–8 (80 %)
Rope triceps pushdowns	4	7–8 (80 %)
Crunches	3	7–8 (80 %)
Sitting twists	3	7–8 (80 %)

* before the main series, complete a series with 20% and 40% 1RM

Contact Information:

Jan Caha
Faculty of Sport Education – Masaryk university
Kamenice 753/5, 62500 Brno – Bohunice
Mail: 259591@mail.muni.cz