Systematic Review

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MORPHOLOGICAL ADAPTATIONS IN RESPONSE TO CHRONIC EXERCISE ACROSS MUSCULOSKELETAL TISSUES: A SYSTEMATIC REVIEW[1]

ADAPTACIONES MORFOLÓGICAS EN RESPUESTA AL EJERCICIO CRÓNICO EN LOS TEJIDOS OSTEOMUSCULARES: UNA REVISIÓN SISTEMÁTICA

ADAPTAÇÕES MORFOLÓGICAS EM RESPOSTA AO EXERCÍCIO CRÔNICO NOS TECIDOS OSTEOMUSCULARES: UMA REVISÃO SISTEMÁTICA

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ABSTRACT

León, F., Mestre. A., Priego, L., & Vera, J.C. (2023). Morphological adaptations in response to chronic exercise across musculoskeletal tissues: a systematic review. **PENSAR EN MOVIMIENTO: Revista de Ciencias del Ejercicio y la Salud, 21**(1), 1-28. To date, there is no systematic review that summarizes the morphological adaptations of the musculoskeletal system in response to chronic exercise. This systematic review selected original articles

[1] This article has a Spanish version. Available in: León, F., Mestre, A., Priego, L., & Vera, J. C. (2023). [Traducción al español] Adaptaciones morfológicas en respuesta al ejercicio crónico en los tejidos osteomusculares: una revisión sistemática. ***Pensar en Movimiento: Revista de Ciencias del Ejercicio y la Salud, 21***(2), e56159. https://doi.org/10.15517/pensarmov.v21i2.56159

published in English between 2000 and 2020, with a clear exercise intervention and presenting a morphological change in the tissue under study, and covering human participants irrespective of age, gender or health condition. In total, 2819 records were identified. After removal of duplicates, title and abstract screening and full-text review, 67 records were included in the final analysis (6 for inter-vertebral disc, 6 for cartilage, 36 for bone, 2 for ligament, 9 for tendon and 7 for muscle). The most used interventions were aerobic, resistance, and plyometric exercise. Population ranged from children and healthy active people to individuals with a health condition. In conclusion, as a response to chronic exercise there are morphological adaptations in the tissues of the musculoskeletal system which vary from increased stiffness to an increase in cross-sectional area. Although tissues can adapt, several questions still linger, such as optimal dose and type of exercise, whether adaptations can occur in an injured tissue, and functional implications of these adaptations. Future research should address these questions.

Keywords: musculoskeletal system physiology, adaptation, morphology, lifestyle, physical activity

RESUMEN

León, F., Mestre. A., Priego, L. y Vera, J.C. (2023). Adaptaciones morfológicas en respuesta al ejercicio crónico en los tejidos osteomusculares: una revisión sistemática. **PENSAR EN MOVIMIENTO: Revista de Ciencias del Ejercicio y la Salud, 21**(1), 1-28. Hasta la fecha, no existe una revisión sistemática que resuma las adaptaciones morfológicas del sistema osteomuscular en respuesta al ejercicio crónico. Esta revisión sistemática seleccionó artículos originales, con fecha de publicación de 2000 a 2020, idioma de publicación en inglés, con una clara intervención de ejercicio y que presentaron un cambio morfológico en el tejido estudiado. Participantes humanos independientemente de la edad, el género o condición de salud. Se identificaron 2819 registros. Después de eliminar los duplicados, la selección de títulos y resúmenes y la revisión de texto completo, se incluyeron 67 registros en el análisis final (6 para disco intervertebral, 6 para cartílago, 36 para hueso, 2 para ligamento, 9 para tendón y 7 para músculo). Los resultados destacan que las intervenciones más utilizadas fueron ejercicio aeróbico, contra resistencia y pliométrico. La población abarcó desde niños y personas sanas activas hasta personas con alguna condición de salud. Se concluye que como respuesta al ejercicio crónico existen adaptaciones morfológicas en los tejidos del sistema musculoesquelético, que pueden variar desde un aumento de rigidez hasta un aumento de área. Aunque los tejidos pueden adaptarse, aún quedan varias preguntas, como la dosis y tipo de ejercicio óptimo, si pueden ocurrir adaptaciones en un tejido lesionado y las implicaciones funcionales de estas adaptaciones. La investigación futura debe abordar estas preguntas.

Palabras clave: osteomuscular, adaptación, estilo de vida, actividad física.

RESUMO

León, F., Mestre. A., Priego, L. e Vera, J.C. (2023). Adaptações morfológicas em resposta ao exercício crônico nos tecidos osteomusculares: uma revisão sistemática. **PENSAR EN MOVIMIENTO: Revista de Ciencias del Ejercicio y la Salud, 21**(1), 1-28. Até o momento, não há uma revisão sistemática que resuma as adaptações morfológicas do sistema osteomuscular em resposta ao exercício crônico. Esta revisão sistemática selecionou artigos originais, com data de publicação de 2000 a 2020, idioma de publicação em inglês, com clara intervenção de exercícios e que apresentaram alteração morfológica no tecido estudado. Participantes humanos, independentemente da idade, sexo ou condição de saúde. Foram identificados 2.819 registros. Após eliminar os artigos duplicados, triagem de título e resumo e revisão do texto completo, 67 registros foram incluídos na análise final (6 para disco intervertebral, 6 para cartilagem, 36 para osso, 2 para ligamento, 9 para tendão e 7 para músculo). Os resultados destacam que as intervenções mais utilizadas foram exercícios aeróbicos, resistidos e pliométricos. A população variou de crianças e pessoas saudáveis ativas a pessoas com alguma condição de saúde. Conclui-se que, em resposta ao exercício crônico, ocorrem adaptações morfológicas nos tecidos do sistema musculoesquelético, que podem variar desde um aumento de rigidez até um aumento de área. Embora os tecidos possam se adaptar, várias questões permanecem, como a dose ideal e o tipo de exercício, se adaptações podem ocorrer no tecido lesado e as implicações funcionais dessas adaptações. Pesquisas futuras devem abordar essas questões.

Palavras-chave: osteomuscular, adaptação, estilo de vida, atividade física.

Musculoskeletal tissue is highly sensitive to mechanical forces. These mechanical forces can influence cell signaling (Salvi & DeMali, 2018) and drive cellular responses (Dunn & Olmedo, 2016) which, in turn, controls and regulates responses and behaviors in human physiology (Wang, 2017). One type of mechanical forces are the ones experienced during exercise.

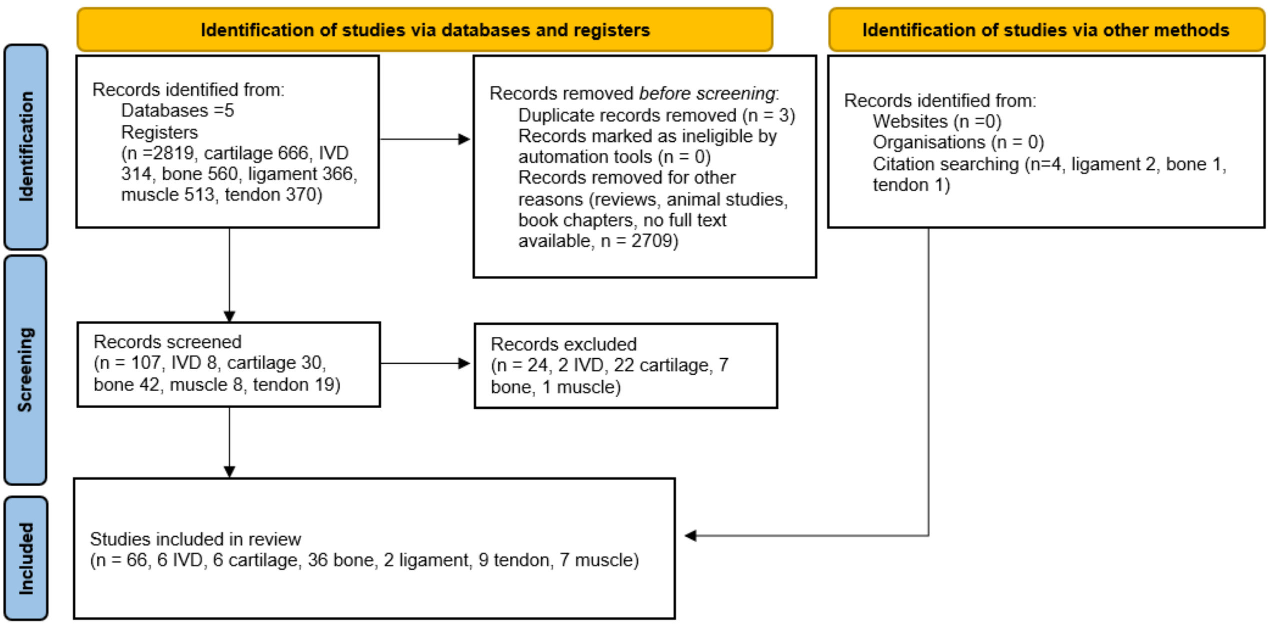
Exercise is typically classified into resistance and aerobic exercise (Wilson et al., 2012). Resistance exercise is designed to enhance muscular strength and power (Stricker et al., 2020) while on the other hand, aerobic exercise aims to improve general endurance performance (Rothschild & Bishop, 2020). Both types of exercise promote adaptations in the musculoskeletal tissues, by altering signaling pathways in charge of protein synthesis (Coffey & Hawley, 2007). A single bout of aerobic exercise is insufficient to produce significant changes to musculoskeletal tissue. Nonetheless, one exercise session promotes transient disturbances in cellular homeostasis that, when repeated over time, result in the specific exercise-induced adaptation associated with long-term training (Coffey et al., 2009; Hughes, Ellefsen, et al., 2018).

Studies have shown the effects of exercise on the morphology of the musculoskeletal system, however, to date there is no systematic review that summarizes the effects of exercise in the morphology of tissues of the musculoskeletal system. This may help guide clinical decision making when looking to elicit changes in the musculoskeletal tissues. As a primary endpoint the aim of this systematic review is to summarize the current body of knowledge regarding the morphological adaptations of the musculoskeletal system in response to chronic exercise and, as a secondary endpoint, to identify the types of exercise used to elicit said morphological adaptations.

METHODS

This review was done according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021). PROSPERO ID CRD42020188000. Studies were eligible for inclusion if they were original articles, publication date from 2000 to 2020, done in human subjects, English as publication language, had a clear exercise intervention and as an outcome presented a morphological adaptation in the tissue studied. Search was done between July 2021 and September 2021. Databases used were Pubmed, PEDro, ClinicalKey, Proquest and ResearchGate. Studies detailing acute changes were excluded. Search strategy was done using keywords and boolean operators: [(Cartilage OR Intervertebral Disc OR Bone OR Ligament OR Tendon OR Muscle) AND Exercise]. All authors contributed to the initial search and screening. FL and AM performed the complete analysis per record. In the event of a disagreement a third author (LP or JCV) was called to settle a decision. The AXIS tool was used for observational studies for risk of bias assessment (Downes et al., 2016). For experimental studies, the PEDro scale was used for risk of bias assessment (Maher et al., 2003). Records were not excluded based on the assessment. Items extracted were the following: author, year of publication, study design, tissue studied, population, intervention, comparison, and outcome.

RESULTS



A total of 2819 records were identified (314 for intervertebral disc (IVD), 666 for cartilage, 561 for bone, 366 for ligament 513 for muscle and 370 for tendon). After full-text screening 66 records were included in the final analysis (6 for IVD, 6 for cartilage, 36 for bone, 2 for ligament, 9 for tendon and 7 for muscle). PRISMA flowchart is presented in Figure 1. León et al. (2023).

Figure 1. PRISMA flowchart of search strategy. Source: the authors.

Characteristics per tissue

A full list detailing each study characteristic (author, design, population, intervention, comparison and outcomes) is presented in the Appendix.

Study design

For IVD four studies were observational in design while two were experimental; for cartilage all six studies were experimental; for bone twenty-five studies were experimental and eleven were observational; for ligament both studies were observational; for tendon four were experimental and five were observational; for muscle all seven studies were experimental.

Population studied

For IVD the population studied were people that partake in sports (4) and individuals with pain (non-specific chronic low back pain (1) and radicular leg pains due to lumbar disc herniation(1)); for cartilage they were asymptomatic marathon beginners (1), women aged 45-55 years of age (1) and participants with osteoarthritis (OA)(4); for bone they were healthy participants (8), children (7), postmenopausal women (5), premenopausal women (3), participants with spinal cord injury (SCI)(2), men with prostate cancer (1), breast cancer survivors with treatment-related menopause (1), community-dwelling individuals with stroke (1), older caucasian participants (2), adult (1) and children (1) tennis players, men with osteopenia or osteoporosis (1), female weightlifters (1) and US female (1) and British male (1) army recruits; for ligament, people studied were female soccer players (1) and male weightlifters (1); for tendon they were basic infantry recruits (1), old female adults (1), participants not strength trained (1), male adults (1) recreationally active volunteers (1) and healthy subjects (4); for muscle, they were premenopausal women with fibromyalgia (FM)(1), young men (1), sedentary men (1), young active men (1) and healthy subjects (3).

Characteristics of intervention

For IVD there was no intervention (observational studies) (4), core exercises (1) and resistance and aerobic exercise (1); for cartilage there was a home exercise program (1) a running program and a marathon (1), aerobic and step aerobic exercise (1), aquatic resistance exercises (1) and a comparison between three types of exercise (2); for bone there was aerobic exercise (1), aqua fitness exercises (1), ordinary curriculum physical activity classes (3), basic military training (2), tennis (1), functional electric rowing (FES) (1), single leg drop exercises (1), high impact unilateral exercises (1), general exercise plus supplementation (1), exercise and hormone therapy (1), multicomponent exercise training (1), odd impact and resistance exercise (1), a combination of resistance, impact and balance exercises (1), high intensity progressive resistance and impact exercises (1), two exercises regimes (1), high-intensity progressive resistance training (1), progressive, moderate-intensity resistance plus impact exercises (2), impact and plyometric exercises (1), no intervention (observational studies)(7) and the rest were a combination of general exercise (7); for ligament both studies were observational, so no intervention as used; for tendon there was basic infantry training (1), plantar flexion exercises (1), isometric plantar flexion (2) explosive isometric unilateral plantar flexion (1), and no intervention (observational studies)(4); for muscle there was total body resistance exercises (1), unilateral resistance exercises (1), leg press exercises (2), bilateral flywheel squats (1), knee extensor exercises (1) and eccentric knee exercise (1).

Comparison

For IVD the comparison was with no sport controls (2), different activity levels (2), core exercises (1) and manual therapy and motor control (1); for cartilage there was a simple control group (1) supplementation (glucosamine sulphate)(1), usual care (1), no training (1) and three types of exercise (2); for bone there was aqua fitness training with control (1) weekly physical activity done in different frequencies (3), between playing arms tennis players (1), tennis in different populations (1), plyometrics in different frequencies (1), drop landing exercises (1), female weightlifters and age matched controls (1), lifetime bone loading (1), exercise plus supplementation (1), between gymnasts and non-gymnasts (1), between types of high intensity training (1), between resistance, balance or jumping exercises (1), FES rowing plus zoledronic acid (1), between exercise and hormone replacement therapy (HRT)(1), a comparison between fine and gross motor activities plus supplementation (calcium)(1), aerobic, resistance and balance exercise compared to upper extremity exercise as control (1), sports with different impact patterns (1), standing hip adduction and abduction, squat and deadlift and a control group (1), resistance exercise, soccer and a control group (1), progressive, moderate-intensity resistance and flexibility training as control (2), lower body resistance plus jumping or upper resistance plus jumping exercise and a control group (1), only exercise training and a control group (1), no comparison (6) and a control group alone (4); for ligament there was no comparison (1) and age-matched controls (1); for tendon there was no exercise as control (2), two exercise regimes with no exercise as control (1), four types of jumping sports (1), elite international level jumping track athletes and healthy recreationally active controls (1), two types of sports and sedentary subjects (1), two types of exercise regime and no specific training as control (1), male runners, female runners and female non-runners(1) and no comparison (1); for muscle there was between men and woman (1), young and old participants (1) concentric and eccentric contractions (2), heavy and low load (1), different velocities and no exercise as controls (1) and healthy women as controls (1).

Outcomes

The most Reported outcomes for IVD were higher IVD in 5 studies and higher T2 values in 3 studies; for cartilage, an increase in thickness (2) and decrease in thickness (2); for bone there were increases in bone mineral density (BMD) (20), increases in bone mineral content (BMC) (10) and increases in cortical area (6); for ligament were increase in cross sectional area (CSA) (1) and increase in volume (1); for tendon there were increases in CSA (6), increases in stiffness (5); for muscle there were increases in mass (4) and increases in CSA (2).

Risk of bias of observational studies per tissue

Characteristics of risk of bias for observational studies are presented in Table 1.

For IVD all criteria were met; only one study had a sample size calculation (Bowden et al., 2018).

For bone all criteria were met; only two studies had non-responders and both had measures undertaken to address non-responders described, response rate described and information about non-responders (Hughes, Gaffney-Stomberg, et al., 2018; O'Leary et al., 2019).

For ligament all criteria were met; only one did not discuss limitations of the study and did not attain ethical approval nor informed consent (Grzelak et al., 2012).

For tendon all criteria were met; three had measures undertaken to address non-responders, response rate described and information about non-responders (Karamanidis & Epro, 2020; Milgrom et al., 2014; Westh et al., 2007) and one had justified its sample size and no clear statistical significance (Milgrom et al., 2014).

All the included studies regarding muscle and cartilage corresponded to experimental designs; therefore, no assessment for observational studies was performed.

Table 1.
Risk of bias assessment for observational studies using the AXIS tool. N/A, non-applicable as there were no non-responders.

Authors	Clear aims	Correct study designs	Sample size	Population defined	Sample appropriate to represent the target population	Selection process appropriate	Measures undertaken to adress non responders	Risk factors and outcome variables measured appropriately to the aims	Clear statistical signific	Method descri	Basic data described	Response rate described	Information about non responders described	Results internally consistent	Presence of results for the analyses described	Discussion and conclusions justified	Limitations discussed	Funding or conflict of interests that could affect results	Ethical approval or informed consent attained
Intervertebral disc																			
Belavy et al. (2017)	YES	YES	NO	YES	YES	YES	N/A	YES	YES	YES	YES	YES	N/A	YES	YES	YES	YES	NO	YES
Belavy et al. (2019)	YES	YES	NO	YES	YES	YES	N/A	YES	YES	YES	YES	YES	N/A	YES	YES	YES	YES	NO	YES
Owen et al. (2021)	YES	YES	NO	YES	YES	YES	N/A	YES	YES	YES	YES	YES	N/A	YES	YES	YES	YES	NO	YES
Bowden et al. (2018)	YES	YES	YES	YES	YES	YES	N/A	YES	YES	YES	YES	YES	N/A	YES	YES	YES	YES	NO	YES
Bone																			
Bailey et al. (2010)	YES	YES	NO	YES	YES	YES	N/A	YES	YES	YES	YES	N/A	N/A	YES	YES	YES	YES	NO	YES
Dowthwaite et al. (2007)	YES	YES	NO	YES	YES	YES	N/A	YES	YES	YES	YES	N/A	N/A	YES	YES	YES	YES	NO	YES
Draghici et al. (2019)	YES	YES	NO	YES	YES	YES	N/A	YES	YES	YES	YES	N/A	N/A	YES	YES	YES	YES	NO	YES
Ducher et al. (2011)	YES	YES	NO	YES	YES	YES	N/A	YES	YES	YES	YES	N/A	N/A	YES	YES	YES	NO	NO	YES

Authors	Clear aims	Correct study designs	Sample size	Population defined	Sample appropriate to represent the target population	Selection process appropriate	Measures undertaken to adress non responders	Risk factors and outcome variables measured appropriately to the aims	Clear statistical signific	Method descri	Basic data described	Response rate described	Information about non responders described	Results internally consistent	Presence of results for the analyses described	Discussion and conclusions justified	Limitations discussed	Funding or conflict of interests that could affect results	Ethical approval or informed consent attained
Ducher et al. (2009)	YES	YES	NO	YES	YES	YES	N/A	YES	YES	YES	YES	N/A	N/A	YES	YES	YES	YES	NO	YES
Ducher et al. (2004)	YES	YES	NO	YES	YES	YES	N/A	YES	YES	YES	YES	N/A	N/A	YES	YES	YES	YES	NO	YES
Heinonen et al. (2002)	YES	YES	NO	YES	YES	YES	N/A	YES	YES	YES	YES	N/A	N/A	YES	YES	YES	YES	NO	YES
Hughes, Gaffney-Stomberg et al. (2018)	YES	YES	NO	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	NO	YES
Nilsson et al. (2013)	YES	YES	NO	YES	YES	YES	N/A	YES	YES	YES	YES	N/A	N/A	YES	YES	YES	YES	NO	YES
O´Leary et al. (2019)	YES	YES	NO	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	NO	YES
Rantalainen et al. (2011)	YES	YES	NO	YES	YES	YES	N/A	YES	YES	YES	YES	N/A	N/A	YES	YES	YES	YES	NO	YES
Ligament																			
Grzelak et al. (2012)	YES	YES	NO	YES	YES	YES	N/A	YES	YES	YES	YES	N/A	N/A	YES	YES	YES	NO	NO	NO
Myrick et al. (2019)	YES	YES	NO	YES	YES	YES	N/A	YES	YES	YES	YES	N/A	N/A	YES	YES	YES	YES	NO	YES
Tendon																			

Authors	Clear aims	Correct study designs	Sample size	Population defined	Sample appropriate to represent the target population	Selection process appropriate	Measures undertaken to adress non responders	Risk factors and outcome variables measured appropriately to the aims	Clear statistical signific	Method descri	Basic data described	Response rate described	Information about non responders described	Results internally consistent	Presence of results for the analyses described	Discussion and conclusions justified	Limitations discussed	Funding or conflict of interests that could affect results	Ethical approval or informed consent attained
Epro et al.(2019)	YES	YES	NO	YES	YES	YES	N/A	YES	YES	YES	YES	N/A	N/A	YES	YES	YES	NO	NO	YES
Karamanidis and Epro (2020)	YES	YES	NO	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	NO	NO	YES
Milgrom et al. (2014)	YES	YES	YES	YES	YES	YES	YES	YES	NO	YES	YES	YES	YES	YES	YES	YES	NO	NO	YES
Westh et al. (2007)	YES	YES	NO	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	NO	NO	YES
Zhang et al. (2015)	YES	YES	NO	YES	YES	YES	N/A	YES	YES	YES	YES	N/A	N/A	YES	YES	YES	NO	NO	YES

Source: the authors

Risk of bias of experimental studies per tissue

Characteristics of risk of bias for experimental studies is presented in Table 2.

For IVD one study had a 6/10 score (Khanzadeh et al., 2020) and one had a score of 7/10 (Owen et al., 2020).

For cartilage one study had a 9/10 score (Armagan et al., 2015), one had a score of 8/10 (Munukka et al., 2016), three had a 6/10 score (Benli Küçük, 2017; Cotofana et al., 2010; Koli et al., 2015) and one had a score of 3/10 (Hinterwimmer et al., 2014).

For bone one study had a score of 4/10 (Hasselstrøm et al., 2008) ten records had a score of 5/10 (Detter et al., 2013; Gabr et al., 2016; Greene et al., 2009; Marques et al., 2011, 2013; Milliken et al., 2003; Specker & Binkley, 2003; Vainionpää et al., 2007; Valdimarsson et al., 2006; Wochna et al., 2019), seven had a score of 6/10 (Bailey et al., 2010; Du et al., 2021; Kukuljan et al., 2011; Lambert et al., 2020; Pang et al., 2006; Watson et al., 2015; Winters-Stone & Snow, 2006) and seven had a score of 7/10 (Bolton et al., 2012; Harding et al., 2020; Karinkanta et al., 2007; Lang et al., 2014; Morse et al., 2019; Winters-Stone et al., 2013, 2014).

For tendon three had a score of 5/10 (Arampatzis et al., 2007; Epro et al., 2017; Werkhausen et al., 2018) and one had a score of 6/10 (Bohm et al., 2014).

For muscle four had a score of 5/10 (Bickel et al., 2011; Fernandez-Gonzalo et al., 2014; Franchi et al., 2014; Holm et al., 2008), and three had a score of 6/10 (Franchi et al., 2015; Häkkinen et al., 2002; Marzilger et al., 2020).

The parameters that most of the studies failed to fulfill were allocation concealment, blinding of subjects, blinding of therapists and blinding of assessors. Included studies for ligament tissue corresponded to observational design; therefore, no assessment for experimental studies was performed.

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Table 2.
Risk of bias assessment for experimental studies using the PEDro tool

Authors	Elegibility criteria	Random allocation	Allocation concealment	Baseline similarity	Blinding of subjects	Blinding of therapist	Blinding of assessor	Measures of more than 85% of subjects on key outcome	Results from treatment ,control or "intention to treat"	Between group comparison	Point measure or measure variability on key outcome	Total PEDro score
Intervertebral disc												
Khanzadeh et al. (2020)	NO	YES	NO	YES	NO	NO	NO	YES	YES	YES	YES	6/10
Owen et al. (2020)	YES	YES	NO	YES	NO	NO	YES	YES	YES	YES	YES	7/10
Cartilage												
Armagan et al. (2015)	YES	YES	YES	YES	YES	NO	YES	YES	YES	YES	YES	9/10
Cotofana et al. (2010)	YES	YES	NO	YES	NO	NO	NO	YES	YES	YES	YES	6/10
Hinterwimmer et al. (2014)	YES	YES	NO	YES	NO	NO	NO	YES	YES	YES	YES	6/10
Koli et al. (2015)	YES	YES	NO	YES	NO	NO	NO	YES	YES	YES	YES	6/10
Küçük et al. (2017)	YES	YES	YES	YES	NO	NO	YES	YES	YES	YES	YES	8/10
Munukka et al. (2016)	YES	NO	NO	NO	NO	NO	NO	YES	YES	NO	YES	3/10
Bone												
Alghadir et al. (2016)	YES	NO	NO	YES	NO	NO	NO	YES	YES	YES	YES	5/10
Bailey & Brooke-Wavell (2010)	YES	YES	NO	YES	NO	NO	NO	YES	YES	YES	YES	6/10
Bolton et al. (2012)	YES	YES	YES	YES	NO	NO	NO	YES	YES	YES	YES	7/10
Detter et al. (2013)	YES	NO	NO	YES	NO	NO	NO	YES	YES	YES	YES	5/10

Du et al. (2021)	YES	YES	NO	YES	NO	NO	NO	YES	YES	YES	YES	6/10
Greene et al. (2009)	YES	NO	NO	YES	NO	NO	NO	YES	YES	YES	YES	5/10
Harding et al. (2020)	YES	YES	YES	YES	NO	NO	NO	YES	YES	YES	YES	7/10
Hasselstrøm et al. (2008)	YES	NO	NO	YES	NO	NO	NO	NO	YES	YES	YES	4/10
Karinkanta et al. (2007)	YES	YES	NO	YES	NO	NO	YES	YES	YES	YES	YES	7/10
Kukuljan et al. (2011)	YES	YES	NO	YES	NO	NO	NO	YES	YES	YES	YES	6/10
Lambert et al. (2020)	YES	YES	NO	YES	NO	NO	NO	YES	YES	YES	YES	6/10
Lang et al. (2014)	YES	YES	NO	YES	YES	NO	NO	YES	YES	YES	YES	7/10
Marques et al. (2011)	YES	NO	NO	YES	NO	NO	NO	YES	YES	YES	YES	5/10
Marques et al. (2013)	YES	YES	NO	YES	NO	NO	NO	NO	YES	YES	YES	5/10
Milliken et al. (2003)	YES	NO	NO	YES	NO	NO	NO	YES	YES	YES	YES	5/10
Morse et al. (2019)	YES	YES	NO	YES	NO	NO	NO	YES	YES	YES	YES	7/10
Pang et al. (2006)	YES	YES	NO	YES	NO	NO	NO	YES	YES	YES	YES	6/10
Specker & Binckley (2003)	YES	YES	NO	YES	NO	NO	NO	NO	YES	YES	YES	5/10
Vainionpää et al. (2007)	YES	YES	NO	YES	NO	NO	NO	NO	YES	YES	YES	5/10
Valdimarsson et al. (2006)	YES	NO	NO	YES	NO	NO	NO	YES	YES	YES	YES	5/10
Watson et al. (2015)	YES	YES	NO	YES	NO	NO	NO	YES	YES	YES	YES	6/10
Winters-Stone et al. (2014)	YES	YES	NO	YES	YES	NO	NO	YES	YES	YES	YES	7/10
Winters-Stone et al. (2013)	YES	YES	YES	YES	NO	NO	NO	YES	YES	YES	YES	7/10
Winters-Stone & Snow	YES	YES	NO	YES	NO	NO	NO	YES	YES	YES	YES	6/10
(2006)	YES	NO	NO	YES	NO	NO	NO	YES	YES	YES	YES	5/10
Tendon												
Arampatzis et al. (2007)	YES	NO	NO	YES	NO	NO	NO	YES	YES	YES	YES	5/10

Bohm et al. (2014)	NO	YES	NO	YES	NO	NO	NO	YES	YES	YES	YES	6/10
Epro et al (2017)	YES	NO	NO	YES	NO	NO	NO	YES	YES	YES	YES	5/10
Werkhausen et al. (2018)	YES	NO	NO	YES	NO	NO	NO	YES	YES	YES	YES	5/10
Muscle												
Bickel et al. (2011)	YES	NO	NO	YES	NO	NO	NO	YES	YES	YES	YES	5/10
Fernandez-Gonzalo et al. (2014)	YES	NO	NO	YES	NO	NO	NO	YES	YES	YES	YES	5/10
Franchi et al. (2014)	YES	YES	NO	YES	NO	NO	NO	YES	YES	YES	YES	6/10
Franchi et al. (2015)	YES	NO	NO	YES	NO	NO	NO	YES	YES	YES	YES	5/10
Häkkinen et al. (2002)	YES	YES	NO	YES	NO	NO	NO	YES	YES	YES	YES	6/10
Holm et al. (2008)	YES	NO	NO	YES	NO	NO	NO	YES	YES	YES	YES	5/10
Marzilger et al. (2020)	NO	YES	NO	YES	NO	NO	NO	YES	YES	YES	YES	6/10

Source: the authors

DISCUSSION

This systematic review aimed to summarize the current body of knowledge regarding morphological adaptations in the tissues of the musculoskeletal system in response to chronic exercise and, as a secondary endpoint, to identify the types of exercise best suited to elicit morphological adaptations. A visual summary of the results is presented in Figure 2.

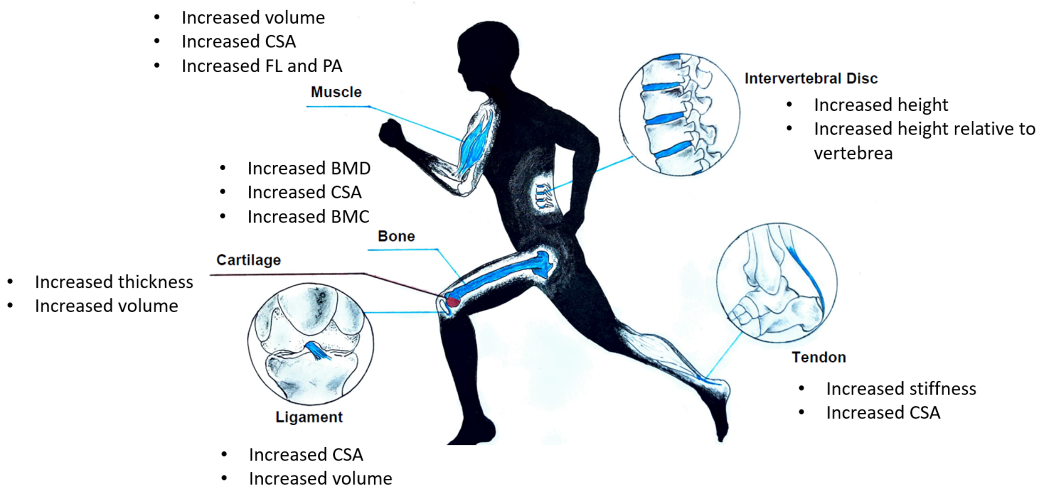

Figure 2. Effects of chronic exercise on musculoskeletal tissues. Source: the authors

Four studies showed changes in IVD parameters including increased height, higher IVD height relative to vertebral body and better IVD hydration. These adaptations occurred mainly as a response to aerobic exercise. The IVD is divided into two substructures: the nucleus pulposus (NP), providing resistance to compressive forces, and the annulus fibrosus (AF), providing resistance to tension forces. Compression and tension forces are known to trigger anabolic responses such as rearrangement of the cytoskeleton and gene expression (Fearing et al., 2018; Iatridis et al., 2006). Accordingly, in the studies that showed differences in IVD parameters, the population engaged in activities that involved dynamic compression moments in the spine such as jumping, walking or running; it could be the case that aerobic exercise, due to its dynamic compression element, is best suited to elicit a response in the IVD. Two studies did not find changes in IVD height after the intervention. Khanzadeh et al. (2020) didn't find any changes after the intervention consisting of suspension exercises. Although the AF is sensitive to tension forces, it appears that, due to the higher water content in the NP, the responses to exercise are most noticeable in the NP and not the AF. Taking this into consideration, the intervention used might not be appropriate to elicit a response in the IVD. Owen et al. (2020) found differences in IVD height and T2 times, but these didn't reach statistical significance. The authors hypothesize that this may be due to poor exercise adherence and duration of the intervention.

Four studies showed changes in cartilage thickness, volume and a better collagen orientation. These changes were observed as a result of resistance and aerobic exercise. Although not fully understood, it is known that the mechanisms by which the cartilage adapts to mechanical forces is an interaction between the pericellular matrix (PCM) and the chondrocyte. The PCM provides a connection between the extracellular matrix (ECM) and the chondrocyte and houses growth factors and regulatory molecules that bind to the receptors in the chondrocyte in response to mechanical loading such as fibroblast growth factor 2 (FGF2).

Meanwhile the chondrocyte is the actual mechanoresponsive organ, housing mechanoreceptors sensitive to the molecules released by the PMC such as ion channels, primary cilia and integrins. This interaction between PCM and the chondrocyte provokes a rearrangement of the cytoskeleton, activation of mitogen-activated protein kinases (MAPK), secretion of Wnts family glycoproteins and expression of MicroRNAs (miRNAs) (Gilbert & Blain, 2018; Vincent & Wann, 2019; Zhao et al., 2020). One study found no changes in cartilage morphology after the intervention. Cotofana et al. (2010) found no change in knee cartilage morphology after three months of intervention. The authors addressed the duration of the intervention as a limitation in their study, which could be the reason for the lack of changes observed, suggesting that three months is too short of a time frame for the cartilage to adapt. In line with this, studies included in this systematic review that observed changes in the cartilage had intervention times of four, six and twelve months. One study found a decrease in cartilage thickness and volume after the intervention period. Hinterwimmer et al. (2014) had a six-month intervention period of marathon supervised training and a marathon run after the intervention period and found a decrease in cartilage thickness and volume. MRI examination times may explain the results observed. The follow up measure was performed one day after the marathon which could represent an acute response to exercise. As an acute response to exercise, cartilage thickness decreases in a dose-dependent manner and the time needed for it to return to baseline levels is unknown (Bini & Bini, 2020; Crowder et al., 2021; Esculier et al., 2019; Harkey et al., 2018; Kersting et al., 2005) so it is possible that the results observed were due to the marathon run. Even considering this the authors interpreted the results as a non-significant decrease in cartilage thickness and volume, indicating that exercise in the form of marathon training and a marathon run is not harmful to cartilage health.

Thirty-six studies reported changes in bone parameters such as increased BMD, CSA, trabecular number, higher cortical area and BMC, with the most reported sites being the hip and spine. These adaptations were observed across different populations and age groups such as healthy people, children, premenopausal women, people with stroke, men with prostate cancer and even individuals with SCI and as a result of resistance, aerobic and plyometric exercises. Bone tissue is known to be sensitive to mechanical loading, triggering different responses such as increasing bone mineral density and strength by stimulation of mesenchymal stem cells, osteoprogenitors, osteoblasts, and the terminally differentiated osteocyte (Yuan et al., 2016). Mechanical stimulation of the bone starts with muscle activity that provokes a slight bend in the bone. This bend initiates fluid flow within the lacuno-canicular network inside the bones which in turn stimulates the osteocyte, triggering bone remodeling (Gusmão & Belangero, 2015; Rosa et al., 2015). Three studies reported no interaction between exercise and bone parameters. Wochna et al. (2019) used a 6-month aqua fitness class intervention in postmenopausal women, and no changes in bone mineral density on the whole body, left hip or spine nor changes in bone turnover markers were observed. The authors reported a small sample size as a limitation in their study which could explain the results obtained. Karinkanta et al. (2007) implemented a 12-month exercise program consisting of resistance training, balance and jumping training, a combination of both, and control group, respectively. Although no changes in BMD were observed, there was an increase in femoral neck strength in both the resistance and combined groups and a 2% less decrease in bone strength index in the combination group compared to the control group at the tibial shaft. The authors hypothesized that this may be due to a redistribution of bone mineral within the femoral neck and tibial shaft in response to exercise and not an increase in bone mineral per se. Greene et al. (2009) used an eight-month drop-landing protocol in prepubertal girls. The protocol consisted of unilateral drop landings with heights of 14 cm and 28 cm. They observed no changes in bone geometry, biomechanical properties nor bone strength index. The authors hypothesized that the reasons no changes were observed were due to the short duration of loading (landing moment), moderate intensity (the relative low heights used) and the lack of variability in movement. The moderate intensity of the drop landings could explain the results observed, as it has been observed in the articles in this review that short duration of loading, like the ones experienced during jogging, and lack of variability in movement, such as the case in plyometric exercises, can provoke changes in bone.

Two studies observed an increase in volume and CSA in the anterior cruciate ligament (ACL) and posterior cruciate ligament (PCL), respectively. It is known that ligament exposure to mechanical loading results in increased stiffness of the tissue (Frank, 2004), although little is known about the specifics of this process. One evidence of mechanical adaptation is the process named “ligamentization”, referring to a change in histological properties a tendon graft undergoes when used for ACL reconstruction where, overtime, the tendon graft starts to resemble more to a normal ACL than to a tendon. These changes in histological properties have been observed in both animal and human studies and could be explained by the mechanical forces the ligament experiences during normal gait and sports activities (Claes et al., 2011; Pauzenberger et al., 2013). The studies included in this review were observational in design and the tissues studied were the ACL and PCL. It could be that the forces experienced in the knee, which are translated into the ACL and PCL, during squatting or running are what triggers adaptation in the ligament.

Nine studies in this review reported changes in the tendon such as increased stiffness and CSA. These adaptations were observed to occur in the patellar and Achilles tendon, in healthy populations, across different age groups and as a result of resistance and aerobic exercise and different sports such as volleyball, basketball, jumping track, field track, among others. The main mechanosensitive cell in the tendon is the tenocyte. The tenocyte is sensitive to mechanical loads through a series of mechanisms and signaling pathways such as primary cilium, intracellular calcium among others (Lavagnino et al., 2015; Munukka et al., 2016), thus, inducing biochemical changes in tendons that affect the diameter of collagen fibrils and CSA (Wang, 2006). There´s still debate whether increased stiffness and CSA may be beneficial or not. For instance, in athletes recovering from patellar tendinopathy, a decrease in stiffness is associated with improved clinical outcome (Breda et al., 2022) whereas other authors have found that greater patellar stiffness may be related to a mechanical improvement in force transmission during muscle contraction (Cristi-Sánchez et al., 2019) and energy storage and release (Wiesinger et al., 2016), and protection from strain injuries (Radovanović et al., 2022).

Seven studies reported changes in the muscle such as an increase in thigh lean mass (TLM), type I and type II fibers, CSA and muscle volume. These adaptations occurred in both women and men, old and young populations and as a result of resistance exercise. Resistance exercise is commonly reported to promote hypertrophy in muscle, with an increase in the muscle CSA (Moghetti et al., 2016). While myosin and actin filaments inside the sarcomere are responsible for muscle contraction, there are a number of possible mechanosensing structures in the sarcomere such as 1) Z-disk, providing a focal point for force transmission between sarcomeres and acting as main anchors during sarcomerogenesis 2) Costameres, acting as focal adhesions inside the skeletal muscle 3) Titin, a protein that lies parallel to the actin and myosin and 4) Filamin-C and Bag3, proteins that reside inside the Z-disk. It has also been proposed that the deformation experienced by the myonuclei as a result of loading of the cytoskeleton, together with the previously mentioned proteins, activates a signaling cascade that triggers adaptation of the muscle (Jani & Schöck, 2009; Wackerhage et al., 2019).

Three studies reported specific adaptations in response to contraction type, in which concentric contractions provoked an increase in pennation angle (PA) while eccentric contractions induced an increase in fascicle length (FL). Although the reasons are not yet understood, and while both types of contractions promote an increase in muscle mass, there seems to be a specific adaptation to contraction type. For instance, as a result of concentric contraction there is an increase of sarcomeres in parallel, thus increasing muscle mid-belly and increasing PA while as a result of eccentric contractions there is an increase in sarcomeres in series, increasing FL (Franchi et al., 2017).

Strengths and limitations

The main strength of this review is that it is the first to summarize the morphological changes in the musculoskeletal system in response to chronic exercise.

Limitations need to be discussed. Firstly, due to the exercise terms often used interchangeably in the literature such as “endurance exercise” or “cardiometabolic exercise” when referring to aerobic exercise, “weight training” or “strength training” when referring to resistance exercise and “physical activity” or “physiological loading” when referring to exercise, it is possible that some articles may not have been included in this review. Secondly, due to the heterogeneity of the studies, such as population or tissue studied and type of exercise intervention, a meta-analysis was not possible.

CONCLUSIONS

Exercise has the capacity to trigger morphological adaptations to tissues of the musculoskeletal system. These adaptations are tissue specific and can range from increased thickness, volume, and stiffness and occur mainly due to aerobic, resistance and plyometric exercise. Although it is clear that tissues can adapt, several questions still linger. The minimal dose required to elicit said adaptations is unknown or what type of exercise is best to trigger said adaptations. Although adaptations have been shown to occur in the presence of pathological changes, such as osteopenia and osteoporosis, it is unknown to what degree these tissues can adapt or even if adaptations can occur while the tissue is injured. Furthermore, there´s still the question whether these adaptations are harmful, such as a thickened ligament or tendon, or if they can be beneficial, like improvements in functional outcomes in sports or general wellbeing or if these adaptations are constant across lifespan. To advance the practice of exercise medicine, future studies should address these questions.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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A-Financing, **B-**Study design, **C-**Data collection, **D-**Statistical analysis and interpretation of results, **E-**Manuscript preparation.

Los autores de este manuscrito son Licenciados en Terapia Física.

REFERENCES

* Included studies in the review.

Alghadir, A., Gabr, S., Al-Eisa, E., & Al-Ghadir, M. (2016). Correlation between bone mineral density and serum trace elements in response to supervised aerobic training in older adults. *Dovepress, 2016*(11), 265-273. https://doi.org/10.2147/CIA.S100566

*Arampatzis, A., Karamanidis, K., & Albracht, K. (2007). Adaptational responses of the human Achilles tendon by modulation of the applied cyclic strain magnitude. *Journal of Experimental Biology*, *210*(Pt 15), 2743–2753. https://doi.org/10.1242/jeb.003814

*Armagan, O., Yilmazer, S., Calısir, C., Ozgen, M., Tascioglu, F., Oner, S., & Akcar, N. (2015). Comparison of the symptomatic and chondroprotective effects of glucosamine sulphate and exercise treatments in patients with knee osteoarthritis. *Journal of Back Musculoskelet Rehabilitation*, *28*(2), 287–293. https://doi.org/10.3233/BMR-140516

*Bailey, C. A., & Brooke-Wavell, K. (2010). Optimum frequency of exercise for bone health: Randomised controlled trial of a high-impact unilateral intervention. *Bone*, *46*(4), 1043–1049. https://doi.org/10.1016/j.bone.2009.12.001

*Bailey, C. A., Kukuljan, S., & Daly, R. M. (2010). Effects of lifetime loading history on cortical bone density and its distribution in middle-aged and older men. *Bone*, *47*(3), 673–680. https://www.sciencedirect.com/science/article/abs/pii/S8756328210013414?via%3Dihub

*Belavy, D. L., Quittner, M. J., Ridgers, N., Ling, Y., Connell, D., & Rantalainen, T. (2017). Running exercise strengthens the intervertebral disc. *Scientific Reports*, *7*, 45975. https://www.nature.com/articles/srep45975

*Belavy, D. L., Quittner, M., Ridgers, N. D., Ling, Y., Connell, D., Trudel, G., & Rantalainen, T. (2019). Beneficial Intervertebral Disc and Muscle Adaptations in High-Volume Road Cyclists. *Medicine & Science in Sports Exercise*, *51*(1), 211–217. https://doi.org/10.1249/MSS.0000000000001770

*Benli Küçük, E., Özyemişci Taşkıran, O., Tokgöz, N., & Meray, J. (2017). Effects of isokinetic, isometric, and aerobic exercises on clinical variables and knee cartilage volume using magnetic resonance imaging in patients with osteoarthritis. *Turkish Journal of Physical Medicine and Rehabilitation*, *64*(1), 8–16. https://doi.org/10.5606/tftrd.2018.795

*Bickel, C. S., Cross, J. M., & Bamman, M. M. (2011). Exercise dosing to retain resistance training adaptations in young and older adults. *Medicine & Science in Sports & Exercise*, *43*(7), 1177–1187. https://doi.org/10.1249/MSS.0b013e318207c15d

Bini, R. R., & Bini, A. F. (2020). Effects of exercise mode in knee cartilage thickness. *Journal* *of Bodywork and Movement Therapies*, *24*(4), 490–495. https://doi.org/10.1016/j.jbmt.2020.05.006

*Bohm, S., Mersmann, F., Tettke, M., Kraft, M., & Arampatzis, A. (2014). Human achilles tendon plasticity in response to cyclic strain: Effect of rate and duration. *Journal of Experimental Biology*, *217*(22), 4010–4017. https://doi.org/10.1242/jeb.112268

*Bolton, K. L., Egerton, T., Wark, J., Wee, E., Matthews, B., Kelly, A., Craven, R., Kantor, S., & Bennell, K. L. (2012). Effects of exercise on bone density and falls risk factors in post-menopausal women with osteopenia: A randomised controlled trial. *Journal of Sciences and Medicine in Sport*, *15*(2), 102–109. https://doi.org/10.1016/j.jsams.2011.08.007

*Bowden, J. A., Bowden, A. E., Wang, H., Hager, R. L., LeCheminant, J. D., & Mitchell, U. H. (2018). In vivo correlates between daily physical activity and intervertebral disc health. *Journal of Orthopaedic Research*, *36*(5), 1313–1323. https://doi.org/10.1002/jor.23765

Breda, S. J., Vos, R.-J. de, Krestin, G. P., & Oei, E. H. G. (2022). Decreasing patellar tendon stiffness during exercise therapy for patellar tendinopathy is associated with better outcome. *Journal of Science and Medicine in Sport*, *25*(5), 372–378. https://doi.org/10.1016/j.jsams.2022.01.002

Claes, S., Verdonk, P., Forsyth, R., & Bellemans, J. (2011). The “ligamentization” process in anterior cruciate ligament reconstruction: What happens to the human graft? A systematic review of the literature. *The American Journal of Sports Medicine*, *39*(11), 2476–2483. https://doi.org/10.1177/0363546511402662

Coffey, V. G., & Hawley, J. A. (2007). The molecular bases of training adaptation. *Sports Medicine*, *37*(9), 737–763. https://link.springer.com/article/10.2165/00007256-200737090-00001

Coffey, V. G., Pilegaard, H., Garnham, A. P., O’Brien, B. J., & Hawley, J. A. (2009). Consecutive bouts of diverse contractile activity alter acute responses in human skeletal muscle. *Journal of Applied Physiology*, *106*(4), 1187–1197. https://doi.org/10.1152/japplphysiol.91221.2008

*Cotofana, S., Ring-Dimitriou, S., Hudelmaier, M., Himmer, M., Wirth, W., Sänger, A. M., & Eckstein, F. (2010). Effects of exercise intervention on knee morphology in middle-aged women: A longitudinal analysis using magnetic resonance imaging. *Cells Tissues Organs*, *192*(1), 64–72. https://doi.org/10.1159/000289816

Cristi-Sánchez, I., Danes-Daetz, C., Neira, A., Ferrada, W., Yáñez Díaz, R., & Silvestre Aguirre, R. (2019). Patellar and Achilles Tendon Stiffness in Elite Soccer Players Assessed Using Myotonometric Measurements. *Sports Health*, *11*(2), 157–162. https://doi.org/10.1177/1941738118820517

Crowder, H. A., Mazzoli, V., Black, M. S., Watkins, L. E., Kogan, F., Hargreaves, B. A., Levenston, M. E., & Gold, G. E. (2021). Characterizing the transient response of knee cartilage to running: Decreases in cartilage T(2) of female recreational runners. *J Orthop Res*, *39*(11), 2340–2352. https://doi.org/10.1002/jor.24994

*Detter, F. T. L., Rosengren, B. E., Dencker, M., Nilsson, J.-Å., & Karlsson, M. K. (2013). A 5-Year Exercise Program in Pre- and Peripubertal Children Improves Bone Mass and Bone Size Without Affecting Fracture Risk. *Calcified Tissue International*, *92*(4), 385–393. https://link.springer.com/article/10.1007/s00223-012-9691-5

Downes, M. J., Brennan, M. L., Williams, H. C., & Dean, R. S. (2016). Development of a critical appraisal tool to assess the quality of cross-sectional studies (AXIS). *BMJ Open*, *6*(12), e011458. http://dx.doi.org/10.1136/bmjopen-2016-011458

*Dowthwaite, J. N., Flowers, P. P. E., Spadaro, J. A., & Scerpella, T. A. (2007). Bone Geometry, Density, and Strength Indices of the Distal Radius Reflect Loading via Childhood Gymnastic Activity. *Journal of Clinical Densitometry*, *10*(1), 65–75. https://doi.org/10.1016/j.jocd.2006.10.003

*Draghici, A. E., Taylor, J. A., Bouxsein, M. L., & Shefelbine, S. J. (2019). Effects of FES-Rowing Exercise on the Time-Dependent Changes in Bone Microarchitecture After Spinal Cord Injury: A Cross-Sectional Investigation. *JBMR Plus*, *3*(9), e10200. https://doi.org/10.1002/jbm4.10200

*Du, J., Hartley, C., Brooke-Wavell, K., Paggiosi, M. A., Walsh, J. S., Li, S., & Silberschmidt, V. V. (2021). High-impact exercise stimulated localised adaptation of microarchitecture across distal tibia in postmenopausal women. *Osteoporosis International*, *32*(5), 907–919. https://link.springer.com/article/10.1007/s00198-020-05714-4

*Ducher, G., Bass, S. L., Saxon, L., & Daly, R. M. (2011). Effects of repetitive loading on the growth-induced changes in bone mass and cortical bone geometry: A 12-month study in pre/peri- and postmenarcheal tennis players. *Journal of Bone and Mineral Research*, *26*(6), 1321–1329. https://doi.org/10.1002/jbmr.323

*Ducher, G., Daly, R. M., & Bass, S. L. (2009). Effects of Repetitive Loading on Bone Mass and Geometry in Young Male Tennis Players: A Quantitative Study Using MRI. *Journal of Bone and Mineral Research*, *24*(10), 1686–1692. https://doi.org/10.1359/jbmr.090415

*Ducher, G., Prouteau, S., Courteix, D., & Benhamou, C. L. (2004). Cortical and trabecular bone at the forearm show different adaptation patterns in response to tennis playing. *Journal of Clinical Densitometry*, *7*(4), 399–405. https://doi.org/10.1385/JCD:7:4:399

Dunn, S. L., & Olmedo, M. L. (2016). Mechanotransduction: Relevance to Physical Therapist Practice-Understanding Our Ability to Affect Genetic Expression Through Mechanical Forces. *Physical Therapy*, *96*(5), 712–721. https://doi.org/10.2522/ptj.20150073

*Epro, G., Hunter, S., König, M., Schade, F., & Karamanidis, K. (2019). Evidence of a Uniform Muscle-Tendon Unit Adaptation in Healthy Elite Track and Field Jumpers: A Cross Sectional Investigation. *Frontiers in Physiology*, *10*, 574. https://doi.org/10.3389/fphys.2019.00574

*Epro, G., Mierau, A., Doerner, J., Luetkens, J. A., Scheef, L., Kukuk, G. M., Boecker, H., Maganaris, C. N., Brüggemann, G.-P., & Karamanidis, K. (2017). The Achilles tendon is mechanosensitive in older adults: Adaptations following 14 weeks versus 1.5 years of cyclic strain exercise. *Journal of Experimental Biology*, *220*(6), 1008–1018. https://doi.org/10.1242/jeb.146407

Esculier, J. F., Jarrett, M., Krowchuk, N. M., Rauscher, A., Wiggermann, V., Taunton, J. E., Wilson, D. R., Gatti, A. A., & Hunt, M. A. (2019). Cartilage recovery in runners with and without knee osteoarthritis: A pilot study. The *Knee Journal*, *26*(5), 1049–1057. https://doi.org/10.1016/j.knee.2019.07.011

Fearing, B. V., Hernandez, P. A., Setton, L. A., & Chahine, N. O. (2018). Mechanotransduction and cell biomechanics of the intervertebral disc. *JOR Spine*, *1*(3). https://doi.org/10.1002/jsp2.1026

*Fernandez-Gonzalo, R., Lundberg, T. R., Alvarez-Alvarez, L., & De Paz, J. A. (2014). Muscle damage responses and adaptations to eccentric-overload resistance exercise in men and women. *European Journal of Applied Physiology*, *114*(5), 1075–1084. https://link.springer.com/article/10.1007/s00421-014-2836-7

*Franchi, M. V., Atherton, P. J., Reeves, N. D., Flück, M., Williams, J., Mitchell, W. K., Selby, A., Beltran Valls, R. M., & Narici, M. V. (2014). Architectural, functional and molecular responses to concentric and eccentric loading in human skeletal muscle. *Acta Physiologica*, *210*(3), 642–654. https://doi.org/10.1111/apha.12225

Franchi, M. V., Reeves, N. D., & Narici, M. V. (2017). Skeletal Muscle Remodeling in Response to Eccentric vs. Concentric Loading: Morphological, Molecular, and Metabolic Adaptations. *Frontiers in Physiology*, *8*(447). https://doi.org/10.3389/fphys.2017.00447

*Franchi, M. V., Wilkinson, D. J., Quinlan, J. I., Mitchell, W. K., Lund, J. N., Williams, J. P., Reeves, N. D., Smith, K., Atherton, P. J., & Narici, M. V. (2015). Early structural remodeling and deuterium oxide-derived protein metabolic responses to eccentric and concentric loading in human skeletal muscle. *Physiological Reports*, *3*(11), e12593. https://doi.org/10.14814/phy2.12593

Frank, C. B. (2004). Ligament structure, physiology and function. *Journal of Musculoskeletal & Neuronal Interactions*, *4*(2), 199–201. https://www.ismni.org/jmni/pdf/16/21FRANK.pdf

*Gabr, S., Al-Ghadir, M., H. Alghadir, A., & S. Al-Eisa, E. (2016). Correlation between bone mineral density and serum trace elements in response to supervised aerobic training in older adults. *Clinical Interventions in Aging*, *2016*(11), 265-273. https://doi.org/10.2147/CIA.S100566

Gilbert, S. J., & Blain, E. J. (2018). Cartilage mechanobiology: How chondrocytes respond to mechanical load. In S. Verbruggen (Ed.), *Mechanobiology in Health and Disease* (pp. 99–126). Academic Press. https://orca.cardiff.ac.uk/id/eprint/114560/

*Greene, D. A., Wiebe, P. N., & Naughton, G. A. (2009). Influence of Drop-Landing Exercises on Bone Geometry and Biomechanical Properties in Prepubertal Girls: A Randomized Controlled Study. *Calcified Tissue International*, *85*(2), 94–103. https://link.springer.com/article/10.1007/s00223-009-9253-7

*Grzelak, P., Podgorski, M., Stefanczyk, L., Krochmalski, M., & Domzalski, M. (2012). Hypertrophied cruciate ligament in high performance weightlifters observed in magnetic resonance imaging. *International Orthopaedics*, *36*(8), 1715–1719. https://link.springer.com/article/10.1007/s00264-012-1528-3

Gusmão, C. V. B. de, & Belangero, W. D. (2015). HOW DO BONE CELLS SENSE MECHANICAL LOADING? *Revista Brasileira de Ortopedia*, *44*(4), 299–305. https://doi.org/10.1016%2FS2255-4971(15)30157-9

*Häkkinen, K., Pakarinen, A., Hannonen, P., Häkkinen, A., Airaksinen, O., Valkeinen, H., & Alen, M. (2002). Effects of strength training on muscle strength, cross-sectional area, maximal electromyographic activity, and serum hormones in premenopausal women with fibromyalgia. *The Journal of Rheumatology*, *29*(6), 1287–1295. https://www.jrheum.org/content/29/6/1287.long

*Harding, A. T., Weeks, B. K., Lambert, C., Watson, S. L., Weis, L. J., & Beck, B. R. (2020). Effects of supervised high-intensity resistance and impact training or machine-based isometric training on regional bone geometry and strength in middle-aged and older men with low bone mass: The LIFTMOR-M semi-randomised controlled trial. *Bone*, *136*, 115362. https://doi.org/10.1016/j.bone.2020.115362

Harkey, M. S., Blackburn, J. T., Hackney, A. C., Lewek, M. D., Schmitz, R. J., Nissman, D., & Pietrosimone, B. (2018). Comprehensively Assessing the Acute Femoral Cartilage Response and Recovery after Walking and Drop-Landing: An Ultrasonographic Study. *Ultrasound Med Biol*, *44*(2), 311–320. https://doi.org/10.1016/j.ultrasmedbio.2017.10.009

*Hasselstrøm, H. A., Karlsson, M. K., Hansen, S. E., Grønfeldt, V., Froberg, K., & Andersen, L. B. (2008). A 3-Year Physical Activity Intervention Program Increases the Gain in Bone Mineral and Bone Width in Prepubertal Girls but not Boys: The Prospective Copenhagen School Child Interventions Study (CoSCIS). *Calcified Tissue International*, *83*(4), 243–250. https://link.springer.com/article/10.1007/s00223-008-9166-x

*Heinonen, A., Sievänen, H., Kannus, P., Oja, P., & Vuori, I. (2002). Site-Specific Skeletal Response to Long-Term Weight Training Seems to be Attributable to Principal Loading Modality: A pQCT Study of Female Weightlifters. *Calcified Tissue International*, *70*(6), 469–474. https://link.springer.com/article/10.1007/s00223-001-1019-9

*Hinterwimmer, S., Feucht, M. J., Steinbrech, C., Graichen, H., & von Eisenhart-Rothe, R. (2014). The effect of a six-month training program followed by a marathon run on knee joint cartilage volume and thickness in marathon beginners. *Knee Surgery Sports Traumatology Arthroscopy*, *22*(6), 1353–1359. https://link.springer.com/article/10.1007/s00167-013-2686-6

*Holm, L., Reitelseder, S., Pedersen, T. G., Doessing, S., Petersen, S. G., Flyvbjerg, A., Andersen, J. L., Aagaard, P., & Kjaer, M. (2008). Changes in muscle size and MHC composition in response to resistance exercise with heavy and light loading intensity. *Journal of Applied Physiology*, *105*(5), 1454–1461. https://doi.org/10.1152/japplphysiol.90538.2008

Hughes, D. C., Ellefsen, S., & Baar, K. (2018). Adaptations to Endurance and Strength Training. *Cold Spring Harbor Perspectives in Medicine*, *8*(6), a029769. http://doi.org/10.1101/cshperspect.a029769

*Hughes, J. M., Gaffney-Stomberg, E., Guerriere, K. I., Taylor, K. M., Popp, K. L., Xu, C., Unnikrishnan, G., Staab, J. S., Matheny, R. W., Jr., McClung, J. P., Reifman, J., & Bouxsein, M. L. (2018). Changes in tibial bone microarchitecture in female recruits in response to 8 weeks of U.S. Army Basic Combat Training. *Bone*, *113*, 9–16. https://www.sciencedirect.com/science/article/abs/pii/S8756328218301753?via%3Dihub

Iatridis, J. C., MacLean, J. J., Roughley, P. J., & Alini, M. (2006). Effects of mechanical loading on intervertebral disc metabolism in vivo. *The Journal of Bone& Joint Surgery*, *88 (Suppl. 2)*, 41–46. https:/doi.org/10.2106/JBJS.E.01407

Jani, K., & Schöck, F. (2009). Molecular mechanisms of mechanosensing in muscle development. *Dev Dyn*, *238*(6), 1526–1534 https://doi.org/10.1002/dvdy.21972

*Karamanidis, K., & Epro, G. (2020). Monitoring Muscle-Tendon Adaptation Over Several Years of Athletic Training and Competition in Elite Track and Field Jumpers. *Frontiers in Physiology*, *11*, 607544. https://www.frontiersin.org/articles/10.3389/fphys.2020.607544/full

*Karinkanta, S., Heinonen, A., Sievänen, H., Uusi-Rasi, K., Pasanen, M., Ojala, K., Fogelholm, M., & Kannus, P. (2007). A multi-component exercise regimen to prevent functional decline and bone fragility in home-dwelling elderly women: Randomized, controlled trial. *Osteoporosis International*, *18*(4), 453–462. https://link.springer.com/article/10.1007/s00198-006-0256-1

Kersting, U. G., Stubendorff, J. J., Schmidt, M. C., & Brüggemann, G. P. (2005). Changes in knee cartilage volume and serum COMP concentration after running exercise. *Osteoarthritis Cartilage*, *13*(10), 925–934. https://doi.org/10.1016/j.joca.2005.06.005

*Khanzadeh, R., Mahdavinejad, R., & Borhani, A. (2020). The Effect of Suspension and Conventional Core Stability Exercises on Characteristics of Intervertebral Disc and Chronic Pain in Office Staff Due to Lumbar Herniated Disc. *The Archives of Bone and Joint Surgery*, *8*(3), 445–453. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7358225/

*Koli, J., Multanen, J., Kujala, U. M., Häkkinen, A., Nieminen, M. T., Kautiainen, H., Lammentausta, E., Jämsä, T., Ahola, R., Selänne, H., Kiviranta, I., & Heinonen, A. (2015). Effects of Exercise on Patellar Cartilage in Women with Mild Knee Osteoarthritis. *Medicine & Science in Sports & Exercise*, *47*(9), 1767–1774. https://doi.org/10.1249/MSS.0000000000000629

Küçük, E.B., Taşkıran, Ö. Ö., Tokgöz, N., & Meray, J. (2018). Effects of isokinetic, isometric, and aerobic exercises on clinical variables and knee cartilage volume using magnetic resonance imaging in patients with osteoarthritis. *Turkish Journal of Physical Medicine and Rehabilitation, 64*(1), 8-16. https://doi.org/10.5606/tftrd.2018.795

*Kukuljan, S., Nowson, C. A., Sanders, K. M., Nicholson, G. C., Seibel, M. J., Salmon, J., & Daly, R. M. (2011). Independent and Combined Effects of Calcium-Vitamin D3 and Exercise on Bone Structure and Strength in Older Men: An 18-Month Factorial Design Randomized Controlled Trial. *The Journal of Clinical Endocrinology & Metabolism*, *96*(4), 955–963. https://doi.org/10.1210/jc.2010-2284

*Lambert, C., Beck, B. R., Harding, A. T., Watson, S. L., & Weeks, B. K. (2020). Regional changes in indices of bone strength of upper and lower limbs in response to high-intensity impact loading or high-intensity resistance training. *Bone*, *132*, 115192. https://doi.org/10.1016/j.bone.2019.115192

*Lang, T. F., Saeed, I. H., Streeper, T., Carballido-Gamio, J., Harnish, R. J., Frassetto, L. A., Lee, S. M., Sibonga, J. D., Keyak, J. H., Spiering, B. A., Grodsinsky, C. M., Bloomberg, J. J., & Cavanagh, P. R. (2014). Spatial Heterogeneity in the Response of the Proximal Femur to Two Lower-Body Resistance Exercise Regimens. *Journal of Bone and Mineral Research*, *29*(6), 1337–1345. https://doi.org/10.1002%2Fjbmr.2155

Lavagnino, M., Wall, M. E., Little, D., Banes, A. J., Guilak, F., & Arnoczky, S. P. (2015). Tendon mechanobiology: Current knowledge and future research opportunities. *Journal of Orthopaedic Research*, *33*(6), 813–822. https://doi.org/10.1002/jor.22871

León, F., Mestre. A., Priego, L., & Vera, J.C. (2023). Full study of Morphological adaptations in response to chronic exercise across musculoskeletal tissues: a systematic review. *Pensar en Movimiento: Revista de Ciencias del Ejercicio y la Salud, 21*(1), 1-21. https://doi.org/10.15517/pensarmov.v21i1.55427

Maher, C. G., Sherrington, C., Herbert, R. D., Moseley, A. M., & Elkins, M. (2003). Reliability of the PEDro Scale for Rating Quality of Randomized Controlled Trials. *Physical*

Therapy, *83*(8), 713–721. https://doi.org/10.1093/ptj/83.8.713
*Marques, E. A., Mota, J., Machado, L., Sousa, F., Coelho, M., Moreira, P., & Carvalho, J. (2011). Multicomponent Training Program with Weight-Bearing Exercises Elicits Favorable Bone Density, Muscle Strength, and Balance Adaptations in Older Women. *Calcified Tissue International*, *88*(2), 117–129. https://link.springer.com/article/10.1007/s00223-010-9437-1
*Marques, E. A., Mota, J., Viana, J. L., Tuna, D., Figueiredo, P., Guimarães, J. T., & Carvalho, J. (2013). Response of bone mineral density, inflammatory cytokines, and biochemical bone markers to a 32-week combined loading exercise programme in older men and women. *Archives of Gerontology and Geriatrics*, *57*(2), 226–233. https://doi.org/10.1016/j.archger.2013.03.014
*Marzilger, R., Bohm, S., Mersmann, F., & Arampatzis, A. (2020). Modulation of physiological cross-sectional area and fascicle length of vastus lateralis muscle in response to eccentric exercise. *Journal of Biomechanics*, *111*, 110016. https://doi.org/10.1016/j.jbiomech.2020.110016
*Milgrom, Y., Milgrom, C., Altaras, T., Globus, O., Zeltzer, E., & Finestone, A. S. (2014). Achilles tendons hypertrophy in response to high loading training. *Foot Ankle International*, *35*(12), 1303–1308. https://doi.org/10.1177/1071100714550651
*Milliken, L. A., Going, S. B., Houtkooper, L. B., Flint-Wagner, H. G., Figueroa, A., Metcalfe, L. L., Blew, R. M., Sharp, S. C., & Lohman, T. G. (2003). Effects of exercise training on bone remodeling, insulin-like growth factors, and bone mineral density in postmenopausal women with and without hormone replacement therapy. *Calcified Tissue International*, *72*(4), 478–484. https://link.springer.com/article/10.1007/s00223-001-1128-5
Moghetti, P., Bacchi, E., Brangani, C., Donà, S., & Negri, C. (2016). Metabolic Effects of Exercise. *Frontiers of Hormone Research*, *47*, 44–57. https://doi.org/10.1159/000445156
*Morse, L. R., Troy, K. L., Fang, Y., Nguyen, N., Battaglino, R., Goldstein, R. F., Gupta, R., & Taylor, J. A. (2019). Combination Therapy With Zoledronic Acid and FES-Row Training Mitigates Bone Loss in Paralyzed Legs: Results of a Randomized Comparative Clinical Trial. *JBMR Plus*, *3*(5), e10167. https://doi.org/10.1002/jbm4.10167
*Munukka, M., Waller, B., Rantalainen, T., Häkkinen, A., Nieminen, M. T., Lammentausta, E., Kujala, U. M., Paloneva, J., Sipilä, S., Peuna, A., Kautiainen, H., Selänne, H., Kiviranta, I., & Heinonen, A. (2016). Efficacy of progressive aquatic resistance training for tibiofemoral cartilage in postmenopausal women with mild knee osteoarthritis: A randomised controlled trial. *Osteoarthritis and Cartilage*, *24*(10), 1708–1717. https://doi.org/10.1016/j.joca.2016.05.007
*Myrick, K. M., Voss, A., Feinn, R. S., Martin, T., Mele, B. M., & Garbalosa, J. C. (2019). Effects of season long participation on ACL volume in female intercollegiate soccer athletes. *Journal of Experimental Orthopaedics*, *6*(1). https://jeo-esska.springeropen.com/articles/10.1186/s40634-019-0182-8
*Nilsson, M., Ohlsson, C., Mellström, D., & Lorentzon, M. (2013). Sport-specific association between exercise loading and the density, geometry, and microstructure of weight-bearing bone in young adult men. *Osteoporosis International*, *24*(5), 1613–1622. https://doi.org/10.1007%2Fs00198-012-2142-3

*O'Leary, T. J., Izard, R. M., Walsh, N. P., Tang, J. C. Y., Fraser, W. D., & Greeves, J. P. (2019). Skeletal macro- and microstructure adaptations in men undergoing arduous military training. *Bone*, *125*, 54–60. https://www.sciencedirect.com/science/article/abs/pii/S8756328219301735?via%3Dihub

*Owen, P. J., Hangai, M., Kaneoka, K., Rantalainen, T., & Belavy, D. L. (2021). Mechanical loading influences the lumbar intervertebral disc. A cross-sectional study in 308 athletes and 71 controls. *Journal of Orthopaedic Research*, *39*(5), 989–997. https://doi.org/10.1002/jor.24809

*Owen, P. J., Miller, C. T., Rantalainen, T., Simson, K. J., Connell, D., Hahne, A. J., Trudel, G., Ford, J. J., & Belavy, D. L. (2020). Exercise for the intervertebral disc: A 6-month randomised controlled trial in chronic low back pain. *European Spine Journal*, *29*(8), 1887–1899. https://link.springer.com/article/10.1007/s00586-020-06379-7

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *The BMJ*, *372*, n71. https://doi.org/10.1136/bmj.n71

*Pang, M. Y. C., Ashe, M. C., Eng, J. J., Mckay, H. A., & Dawson, A. S. (2006). A 19-week exercise program for people with chronic stroke enhances bone geometry at the tibia: A peripheral quantitative computed tomography study. *Osteoporosis International*, *17*(11), 1615–1625. https://doi.org/10.1007%2Fs00198-006-0168-0

Pauzenberger, L., Syré, S., & Schurz, M. (2013). "Ligamentization" in hamstring tendon grafts after anterior cruciate ligament reconstruction: A systematic review of the literature and a glimpse into the future. *Arthroscopy*, *29*(10), 1712–1721. https://doi.org/10.1016/j.arthro.2013.05.009

Radovanović, G., Bohm, S., Peper, K. K., Arampatzis, A., & Legerlotz, K. (2022). Evidence-Based High-Loading Tendon Exercise for 12 Weeks Leads to Increased Tendon Stiffness and Cross-Sectional Area in Achilles Tendinopathy: A Controlled Clinical Trial. *Sports Medicine - Open*, *8*(1), 149. https://sportsmedicine-open.springeropen.com/articles/10.1186/s40798-022-00545-5

*Rantalainen, T., Nikander, R., Daly, R. M., Heinonen, A., & Sievänen, H. (2011). Exercise loading and cortical bone distribution at the tibial shaft. *Bone*, *48*(4), 786–791. https://doi.org/10.1016/j.bone.2010.11.013

Rosa, N., Simoes, R., Magalhães, F. D., & Marques, A. T. (2015). From mechanical stimulus to bone formation: A review. *Medical Engineering & Physics*, *37*(8), 719–728. https://doi.org/10.1016/j.medengphy.2015.05.015

Rothschild, J. A., & Bishop, D. J. (2020). Effects of Dietary Supplements on Adaptations to Endurance Training. *Sports Medicine*, *50*(1), 25–53. https://link.springer.com/article/10.1007/s40279-019-01185-8

Salvi, A. M., & DeMali, K. A. (2018). Mechanisms linking mechanotransduction and cell metabolism. *Current Opinion in Cell Biology*, *54*, 114–120. https://doi.org/10.1016/j.ceb.2018.05.004

*Specker, B., & Binkley, T. (2003). Randomized Trial of Physical Activity and Calcium

Supplementation on Bone Mineral Content in 3- to 5-Year-Old Children. *Journal of Bone and Mineral Research*, *18*(5), 885–892. https://doi.org/10.1359/jbmr.2003.18.5.885

Stricker, P. R., Faigenbaum, A. D., McCambridge, T. M., & COUNCIL ON SPORTS MEDICINE AND FITNESS. (2020). Resistance Training for Children and Adolescents. *Pediatrics*, *145*(6), e20201011. https://doi.org/10.1542/peds.2020-1011

*Vainionpää, A., Korpelainen, R., Sievänen, H., Vihriälä, E., Leppäluoto, J., & Jämsä, T. (2007). Effect of impact exercise and its intensity on bone geometry at weight-bearing tibia and femur. *Bone*, *40*(3), 604–611. https://doi.org/10.1016/j.bone.2006.10.005

*Valdimarsson, Ö., Linden, C., Johnell, O., Gardsell, P., & Karlsson, M. K. (2006). Daily Physical Education in the School Curriculum in Prepubertal Girls during 1 Year is Followed by an Increase in Bone Mineral Accrual and Bone Width—Data from the Prospective Controlled Malmö Pediatric Osteoporosis Prevention Study. *Calcified Tissue International*, *78*(2), 65–71. https://link.springer.com/article/10.1007/s00223-005-0096-6

Vincent, T. L., & Wann, A. K. T. (2019). Mechanoadaptation: Articular cartilage through thick and thin. *The Journal of Physiology, 597*(5), 1271–1281. https://doi.org/10.1113/JP275451

Wackerhage, H., Schoenfeld, B. J., Hamilton, D. L., Lehti, M., & Hulmi, J. J. (2019). Stimuli and sensors that initiate skeletal muscle hypertrophy following resistance exercise. *Journal of Applied Physiology*, *126*(1), 30–43. https://doi.org/10.1152/japplphysiol.00685.2018

Wang, J. H.-C. (2006). Mechanobiology of tendon. *Journal of Biomechanics*, *39*(9), 1563–1582. https://doi.org/10.1016/j.jbiomech.2005.05.011

Wang, N. (2017). Review of Cellular Mechanotransduction. *Journal of Physics D: Applied Physics*, *50*(23), 233002. https://doi.org/10.1088%2F1361-6463%2Faa6e18

*Watson, S. L., Weeks, B. K., Weis, L. J., Horan, S. A., & Beck, B. R. (2015). Heavy resistance training is safe and improves bone, function, and stature in postmenopausal women with low to very low bone mass: Novel early findings from the LIFTMOR trial. *Osteoporosis International*, *26*(12), 2889–2894. https://link.springer.com/article/10.1007/s00198-015-3263-2

*Werkhausen, A., Albracht, K., Cronin, N. J., Paulsen, G., Bojsen-Møller, J., & Seynnes, O. R. (2018). Effect of Training-Induced Changes in Achilles Tendon Stiffness on Muscle-Tendon Behavior During Landing. *Frontiers in Physiology*, *9*, 794. https://doi.org/10.3389%2Ffphys.2018.00794

*Westh, E., Kongsgaard, M., Bojsen-Moller, J., Aagaard, P., Hansen, M., Kjaer, M., & Magnusson, S. P. (2007). Effect of habitual exercise on the structural and mechanical properties of human tendon, in vivo, in men and women. *Scandinavian Journal of Medicine & Science in Sports*, *18*(1), 23–30. https://doi.org/10.1111/j.1600-0838.2007.00638.x

Wiesinger, H.-P., Rieder, F., Kösters, A., Müller, E., & Seynnes, O. R. (2016). Are Sport-Specific Profiles of Tendon Stiffness and Cross-Sectional Area Determined by Structural or Functional Integrity? *PLOS ONE*, *11*(6), e0158441. https://doi.org/10.1371/journal.pone.0158441

Wilson, J. M., Loenneke, J. P., Jo, E., Wilson, G. J., Zourdos, M. C., & Kim, J.-S. (2012). The effects of endurance, strength, and power training on muscle fiber type shifting. *Journal of Strength and Conditioning Research*, *26*(6), 1724–1729. https://doi.org/10.1519/JSC.0b013e318234eb6f

*Winters-Stone, K. M., Dobek, J. C., Bennett, J. A., Maddalozzo, G. F., Ryan, C. W., & Beer, T. M. (2014). Skeletal Response to Resistance and Impact Training in Prostate Cancer Survivors. *Medicine & Science in Sports & Exercise*, *46*(8), 1482–1488. https://doi.org/10.1249/MSS.0000000000000265

*Winters-Stone, K. M., Dobek, J., Nail, L. M., Bennett, J. A., Leo, M. C., Torgrimson-Ojerio, B., Luoh, S.-W., & Schwartz, A. (2013). Impact + resistance training improves bone health and body composition in prematurely menopausal breast cancer survivors: A randomized controlled trial. *Osteoporosis International*, *24*(5), 1637–1646. https://link.springer.com/article/10.1007/s00198-012-2143-2

*Winters-Stone, K. M., & Snow, C. M. (2006). Site-specific response of bone to exercise in premenopausal women. *Bone*, *39*(6), 1203–1209. https://doi.org/10.1016/j.bone.2006.06.005

*Wochna, K., Nowak, A., Huta-Osiecka, A., Sobczak, K., Kasprzak, Z., & Leszczyński, P. (2019). Bone Mineral Density and Bone Turnover Markers in Postmenopausal Women Subjected to an Aqua Fitness Training Program. *International Journal of Environmental Research and Public Health*, *16*(14), 2505. https://doi.org/10.3390/ijerph16142505

Yuan, Y., Chen, X., Zhang, L., Wu, J., Guo, J., Zou, D., Chen, B., Sun, Z., Shen, C., & Zou, J. (2016). The roles of exercise in bone remodeling and in prevention and treatment of osteoporosis. *Progress in Biophysics and Molecular Biology*, *122*(2), 122–130. https://doi.org/10.1016/j.pbiomolbio.2015.11.005

*Zhang, Z. J., Ng, G. Y. F., & Fu, S. N. (2015). Effects of habitual loading on patellar tendon mechanical and morphological properties in basketball and volleyball players. *European Journal of Applied Physiology*, *115*(11), 2263–2269. https://link.springer.com/article/10.1007/s00421-015-3209-6

Zhao, Z., Li, Y., Wang, M., Zhao, S., & Fang, J. (2020). Mechanotransduction pathways in the regulation of cartilage chondrocyte homoeostasis. *J Cell Mol Med*, *24*(10), 5408–5419. https://doi.org/10.1111/jcmm.15204