Review

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The Role of Omega-3 Polyunsaturated Fatty Acids in Muscle Growth and Recovery: Implications for Aging and Performance

Behzad Varamini *, Jonah O. Yang, Benjamin J. Merry and Daniel J. Dau

Biola University, School of Science, Technology, and Health, La Mirada, CA 90639, USA
* Correspondence: behzad.varamini@biola.edu

Abstract: Omega-3 polyunsaturated fatty acids (PUFAs) play a critical yet underappreciated role in muscle health, particularly eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). Through a review of current literature, we analyze the effects of these nutrients on muscle protein synthesis, mass, strength, and recovery. Studies demonstrate that omega-3 PUFAs enhance muscle protein synthesis via the mTOR pathway and possess anti-inflammatory properties that may reduce muscle damage and atrophy, particularly in older adults. Their potential to improve muscle function and mitigate exercise-induced damage is also reviewed, highlighting relevance for athletes and active individuals. Further research on optimal dosages and long-term effects of omega-3 supplementation is needed, providing a basis for future studies and practical recommendations for leveraging these nutrients to support muscle health.

Keywords: omega-3; muscle; growth; recovery; performance; EPA; DHA

1. Introduction

Omega-3 polyunsaturated fatty acids (PUFAs) are a class of unsaturated lipids that have a double bond between the third and fourth carbons from the omega (methyl) end [1]. Of the omega-3 fats, the three most predominantly studied, eicosapentaenoic acid (EPA), docosapentaenoic acid (DPA), and docosahexaenoic acid (DHA), have been shown to have numerous health benefits in humans and animals ranging from cardiovascular health to human development [2].

Of widespread interest, omega-3 PUFAs have been implicated for their ability to attenuate cardiovascular disease risk factors. For example, several key cardiovascular disease risk factors have been shown to be reduced through the supplementation of omega-3 PUFAs [3]. Furthermore, Santurino et al. [4] found that overweight and obese individuals subject to food naturally high in omega-3 PUFAs improved in plasma biomarkers that indicate reduced CVD risk. In heart failure patients, omega-3 PUFA supplementation led to a reduction in recurrent heart failure hospitalizations with an increased effect in patients with type II diabetes mellitus [5].

In addition to cardiovascular disease, omega-3 PUFAs have proven beneficial for various neurological and developmental stages. For example, higher omega-3 PUFA content in plasma phospholipids was correlated to lower rates of subclinical infarcts and better white matter grade on MRI in older adults [6]. In another study, omega-3 PUFAs were found to downregulate inflammatory pathways, leading to a reduction in the severity and frequency of migraines [7]. Similarly, EPA supplementation led to improvement in visual processing recovery and complex reaction time in males and females aged 19-34 [8].

Omega-3 PUFAs also have the ability to modulate many inflammatory pathways, leading to many beneficial effects for human health. Specifically, Omega-3 PUFAs are known to produce specific metabolites with anti-inflammatory properties. In particular, specialized pro-resolving mediators (SPMs) are a class of omega-3-derived anti-inflammatory agents and include resolvins, maresins, and protectins [9]. As such, many researchers consider omega-3 PUFAs a strong therapeutic candidate for diseases caused by inflammation. Studies have identified a pathway by

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which omega-3 PUFAs modulate the production of lipoxygenase and cytochrome P450 - both lipid metabolites known for their anti-inflammatory properties [10]. Similarly, another study described vascular inflammation as the link between omega-3 PUFA supplementation and cardiovascular benefit [11].

Taken together, it is well established that omega-3 PUFAs affect a variety of different biological processes with the potential to positively impact human health. More recently, there has been research focused on understanding omega-3 PUFA's ability to counteract age-related skeletal muscle mass depletion (sarcopenia), and atrophy [12,13]. Additionally, there is research that suggests omega-3 supplementation improves both muscle performance and endurance [14]. The purpose of this current review is to survey the most recent literature relating to omega-3 supplementation and its effects on skeletal muscle growth and recovery. This paper will summarize the effects of omega-3 supplementation on muscle synthesis, sarcopenia, atrophy, and exercise-induced endurance.

2. Omega-3 and Muscle Tissue

It has long been known that muscle growth occurs in 3 different ways: 1) by increasing the number of muscle cells, 2) by increasing the diameter of the muscle fiber, and 3) by increasing the length of the muscle fiber [15]. Different types of stress on muscle tissue are often the strongest signal to stimulate growth, with one of the most well-studied stressors being resistance training. Resistance training follows the rule of progressive overload, which states that increasing the demand on the muscle by increasing workout intensity over time will enable it to grow in response to the stress and corresponding stress and inflammatory signals sent to the muscle from the increased demand [16]. In addition to resistance training, eating adequate protein and obtaining enough sleep is crucial in helping the muscle recover and increase in size. Adequate protein intake supplies the body with a constant supply of amino acids and thus protein synthesis is maximized [17]. Likewise, ample sleep enables the body to repair damaged muscle fibers after an intense workout by maximizing protein synthesis during rest [18].

Recently, research regarding using omega-3 fatty acids as a supplement for muscle growth has become more prominent. In one study examining the effect of omega-3 on muscle loss, 1.86g EPA and 1.50g DHA increased the activation of anabolic signaling proteins that promote muscle synthesis [19]. By increasing muscle protein synthesis, increased muscle strength can also be achieved, as the two are tied together tightly[20]. Based on these studies and many more like them that will be summarized in this paper, the potential exists for omega-3 to hold promise for muscle growth.

In addition to muscle growth, omega-3 PUFAs have more recently been suggested to combat the loss of lean body mass and muscle atrophy. Muscle atrophy refers to a decrease in muscle mass by the wasting away of muscle, often as a result of underuse, aging, or other factors [21]. Omega-3 PUFAs are considered to be a potential therapeutic that combats the negative effects of this muscle wasting especially in elderly populations [22]. Muscle wasting in old age is known to increase the risk of falls and mortality, furthering the importance of solutions that can increase lean body mass in elderly individuals [23].

Finally, while omega-3 PUFAs and their role in the reduction of inflammation is well understood, the effect of inflammation in ways that benefit muscle growth, strength, wasting, and recovery remains understudied and is a more recent area of emerging research. For example, one study found that attenuation of exercise-induced muscle damage may combat the effects of soreness-related exercise avoidance, allowing for more progressive load on muscles which is likely to lead to enhanced muscle growth and strength [24].

Omega-3 fatty acids hold promise for improving outcomes related to muscle growth/strength, muscle loss prevention, and inflammation reduction. In this paper, we examine how omega-3 affects these pathways in a few key demographics, including older adults and athletes.

3. Omega-3 and Muscle Growth

Muscle growth and strength is a key area of interest across many life stages. Increased muscle mass due to resistance exercise has numerous health benefits, including increased bone density, a higher resting metabolic rate, improved movement control, lower blood pressure, and even improved mental health [25].

While a number of dietary factors have been studied in relation to muscle growth and strength, omega-3 fatty acids have interestingly been shown to be a potential factor in increasing muscle growth and strength [26]. Although there is research conducted for all age groups in this area, adults older than 60 have been the primary focus. As humans age, decreased physical activity, along with decrement in the function of the endocrine system and diminished levels of testosterone, estrogen, and growth hormones all contribute to decreasing muscle mass levels [27]. To combat this loss in muscle mass, researchers have been studying whether the use of omega-3 supplementation could provide any aid in increasing the rate of muscle protein synthesis.

Multiple studies have shown that omega-3 supplementation promotes skeletal muscle growth via muscle protein synthesis, an anabolic process by which muscle proteins are synthesized from amino acids. Yoshino et al. have proposed a possible mechanism for omega-3 PUFAs impact on protein anabolism, suggesting that omega-3 supplementation consisting of 1.86 g/day EPA and 1.50 g/day DHA may upregulate the function of the mitochondria and the expression of mTOR, a signaling factor critical to cell growth [28]. In a placebo-controlled study involving 16 male and female participants over the age of 65, researchers observed that the group that was supplemented with the same amounts consisting of 1.86 g/day EPA and 1.50 g/day DHA had higher levels of amino acids in their bloodstream, which was linked to an increase in the rate of muscle protein synthesis [19].

In several other experiments, researchers took a different approach. Instead of directly observing how omega-3 fatty acids could affect muscle protein synthesis rates, they studied whether omega-3 supplementation could increase muscle strength, specifically when paired with resistance training in older adults. In a study that tested the one rep-max (1-RM) of individuals using the single-leg extensor movement, omega-3 supplementation consisting of 4 g/day EPA and DHA was found to have a significant positive effect on the 1-RM compared to the placebo [29]. While the mechanisms behind this benefit are not well understood, researchers proposed that omega-3 fatty acids enhance the body's acute anabolic response to exercise. In addition, omega-3 fatty acids also could upregulate mitochondrial energy metabolism, helping satisfy the energetic demands stemming from muscle contraction [29]. A study in older women that tested 1-RM for single-leg extensor movements had a similar conclusion, as omega-3 supplementation led to 1-RM increases [30]. In further studies concerning older women, it was again shown that a diet high in DHA omega 3's paired with lower-body resistance training led to increases in leg extension 1-RM [31], as well as calf plantar and dorsiflexion strength when supplemented with 0.4 g/day EPA and 0.3 g/day DHA [32]. These strength increases were shown not only in isotonic leg exercises but also in isometric ones, such as the knee-extensor exercise when paired with 0.41 g/day DHA and 0.54 g/day EPA [33]. In similar strength studies, omega-3 supplementation composed of 1.34 g/day EPA and 1.07 g/day DHA was shown to increase hand grip strength [34], and 3 g/day DHA and EPA combined helped maintain hand grip strength in adults with low skeletal muscle mass [20]. In contrast, a study on overweight and obese postmenopausal women aged 55-70 years old found that 1.65 g/day DHA and 0.15 g/day EPA only improved the 1-RM's of the lower limbs, such as those used in the leg press, whereas it did not have any effect on the 1RM's of the upper limbs, such as those used in the chest press [35].

While a preponderance of evidence suggests that omega-3 can help improve 1-RM, two studies remain outliers in this area. In one, older participants were separated into male and female groups and further into omega-3 supplementation or placebo groups, with the observation that only the female group saw significant differences in knee extensor muscle strength, even when both male and female supplementation groups received 2.1 g/day EPA and 0.6 g/day DHA[36]. Interestingly, this contradicted another study that observed significant differences in knee extensor muscle strength in the male group only, with both groups receiving 1.397 g/day DHA, 0.749 g/day EPA, and 0.049 g/day DPA [37]. Collectively, however, there is a positive trend of omega-3 supplementation increasing the muscle strength of older adults.

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While most of the studies focused on the effects of omega-3 fatty acids on muscle growth and strength in older adults due to common muscle loss such as sarcopenia, researchers have also studied this phenomenon in younger adults. In agreement with studies on aged populations, researchers have found that omega-3 fatty acids can also increase muscle strength in younger adults. One study observed 24 healthy men aged between 18 and 20 years old and found that voluntary contraction torque was significantly higher in the group that was supplemented with 0.6 g/day EPA and 0.26 g/day DHA than in the group with the placebo [38]. In another study involving 28 males and females aged 18-40, the bench and squat 1-RM of the group with omega-3 supplementation of 2.275 g/day EPA and 1.575 g/day DHA was significantly higher than the placebo group [39]. One possible mechanism proposed by this study is that omega-3 supplementation increases fast-twitch muscle fiber hypertrophy, and these muscle fibers are the primary movers in higher-intensity movements such as 1-RM attempts. In addition, another possibility includes increased neuromuscular activation due to omega-3 supplementation, which allows more muscle fibers to be recruited, resulting in an increase in muscle strength [39]. In general, and though these studies are more limited, younger adults seem to benefit from omega-3 supplementation in a manner similar to older adults, with a positive impact on muscle growth and strength as commonly measured by 1-RM.

Although there have been a myriad of studies confirming the correlation between omega-3 supplementation and muscle strength and growth, there have also been a few studies suggesting that omega-3 supplementation may not affect muscle growth or strength. In one study, 24 healthy physically active adults between the ages of 60 and 75 were divided into two equal groups, one with the fish oil supplementation and one without. It was found that there was no significant difference in sarcoplasmic reticulum Ca^{2+} ATPase (SERCA) activity between the two groups, even when the supplementation group consumed 2 g/day EPA and 1 g/day DHA [40]. Because a reduction in SERCA activity has been linked to muscle atrophy and weakness [41], the observation that there was no significant difference in SERCA activity between the two groups suggests that omega-3 supplementation did not have a significant effect on muscle growth or strength. It is, of course, crucial to note that this study did not directly measure muscle growth or strength but used SERCA as a corollary. Likewise, in another study involving 1680 participants 70 years or older, no significant long-term differences in leg and handgrip strength were observed between the group who consumed 0.800 g/day DHA and 0.225 g/day EPA and the group who did not [42]. However, these two studies remain outliers, and differences in the study population, duration, and omega-3 sources and dosages could all play a complex role in determining the true effect of omega-3 supplementation on muscle growth and strength.

There seems to be a promising correlation between omega-3 fatty acid supplementation and muscle growth and strength in both younger and older adults, with some studies examining the underlying mechanisms by which these benefits are conferred. However, studies suggest that omega-3 supplementation alone may not induce significant changes and that it is vital to pair omega-3s with resistance exercise for maximal benefit. Overall, omega-3 supplementation can potentially benefit young adults looking to increase their baseline muscle mass and strength, and likewise, older adults seeking to fight sarcopenia and maintain existing muscle mass and strength.

4. Omega-3 and Muscle Atrophy

Omega-3 supplementation has been frequently used for its proven benefits for cardiovascular, metabolic, and mental health [43]. More recently, researchers have begun to study omega-3's potential effects on anabolic and catabolic processes. One such catabolic process that occurs in older adults is sarcopenia. While the use of the term sarcopenia is more recent, it is increasingly important clinically as it has been highly correlated with mobility impairment as well as increases in mortality and morbidity [44]. There is little consensus within the medical community on the treatment of sarcopenia, however physical activity and nutritional interventions are common [45]. While the exact pathophysiology of sarcopenia is not well understood, many believe that it may be partially a result of inflammatory processes due to the upregulation of inflammatory biomarkers observed in sarcopenic individuals [34,46]. Omega-3 PUFAs have been heavily studied for their anti-

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inflammatory properties and ability to directly inhibit the production of inflammatory cytokines [47]. For this reason, omega-3s are mechanistically relevant to the inflammation-related attenuation of sarcopenia.

Several recent studies have explored the potential of omega-3 supplementation for the attenuation of age-related muscle loss. An observational study showed that intake of omega-3 was negatively correlated with symptoms of sarcopenia in a group of older adults [12]. Similarly, experimental studies have attempted to understand the relationship between omega-3 supplementation and sarcopenia. One such study showed a 4% increase in lean mass and a 7% increase in functional capacity in healthy older females supplementing 3g/day of EPA and DHA over 12 weeks as compared to placebo [48]. In one study conducted on healthy older adults at risk for sarcopenia, omega-3 supplementation with 1.86 g/day of EPA and 1.50 g/day of DHA was found to increase thigh muscle volume, hand grip strength, and 1-RM muscle strength over a test period of 6 months [23]. Another study supported these findings by concluding that supplementation of 4 g/day omega-3 PUFA led to modest improvements in skeletal muscle strength as measured by leg lean mass and 1-RM leg extensions [29]. Another study concluded that omega-3 supplementation should be considered for individuals at risk for sarcopenia after 6 months of supplementation led to improved body composition and physical strength. This claim was supported by improvement in thigh circumference, skeletal muscle mass, and muscle strength, after 6 months of fish-oil-derived omega-3 supplementation in a placebo-controlled, double-blind trial [34]. Participants in this study were all over the age of 60, further implicating omega-3 for the prevention of age-related muscle atrophy. Taken together, it is clear that omega-3 supplementation leads to improved muscle mass and strength-related outcomes in older populations at risk for sarcopenia.

While the many aforementioned studies would suggest that omega-3 supplementation is effective in ameliorating the symptoms of sarcopenia, other studies have shown little to no benefit. One such study conducted on elderly sarcopenic individuals showed no effect on muscle mass or grip strength in the omega-3-supplemented group when compared to the control [49]. Clearly, further studies are needed to clarify the current data on omega-3 for sarcopenic individuals to help determine whether omega-3s hold promise for attenuating loss of muscle mass.

Studies exploring omega-3 supplementation for muscle maintenance in younger individuals have shown some promise. One study on healthy young women found that omega-3 supplementation remediated progressive mitochondrial dysfunction related to immobilization, likely contributing to muscle mass and strength maintenance [50]. The authors of this study theorized that the effect of omega-3 supplementation on mitochondrial content, function, and lipid metabolism had downstream effects on muscle mass and strength during immobilization [50]. Another study in healthy young women undergoing a 2-week unilateral limb immobilization showed that supplementation with 5g/d of omega-3 completely prevented the immobilization-induced loss of muscle mass that was seen in the placebo group [13]. In addition, measures of protein synthesis in the muscle tissue of the omega-3 group indicated higher rates of muscle protein synthesis compared to placebo. While only a few studies have looked at omega-3 supplementation in younger individuals for immobilization-induced loss of muscle mass, omega-3 appears to be a relevant therapeutic in this case.

Another group of studies has begun to look at omega-3 supplementation for muscle mass preservation in cancer patients and those with neuromuscular disorders. One study found that 45 days of omega-3 supplementation at 2.5g/d prevented intramuscular fat infiltration evidenced by preserved high radio-density skeletal muscle index in cancer patients undergoing chemotherapy [51]. Another study found that the nutritional intervention of 2.2 g/day of EPA was effective in combating muscle loss in patients undergoing chemotherapy for non-small cell lung cancer when compared to the standard of care [52]. In a population of children with neuromuscular disorders, 6-month supplementation of omega-3 PUFA at 2.9 g/day was found to be correlated with both higher fat mass and lean mass when compared to control [53]. In the same study, they found that the omega-3 supplementation group was far less likely to express insulin resistance at the end of the 6-month

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supplementation period, indicating that omega-3 supplementation was important for healthy metabolic control.

5. Omega-3, Inflammation, and Recovery Inflammation/Recovery Body Section

5.1. Soreness

Muscle soreness is caused by a variety of factors induced by rigorous or eccentric exercise, including lactic acid buildup, tissue damage, and inflammation[54]. Soreness can negatively affect muscle performance, limit range of motion, and reduce maximal torque. Muscle recovery is therefore a necessary progression in the process of rebuilding muscle and repairing tissue damage caused during exercise. Research has demonstrated the positive impact of omega-3 PUFAs on relieving muscle soreness and improving the recovery time of muscle performance [24]. A recent trial investigated the efficacy of omega-3-rich fish oil as a reliever for muscle soreness [55]. The authors supplemented 41 resistance-trained individuals with either 2.0, 4.0, or 6.0 g/day doses of fish oil and assessed them over a series of seven weeks. The study found that omega-3 PUFAs enhanced the recovery time for both vertical jump performance and overall muscle soreness compared to the placebo at 24 hours post-exercise. A second study substantiated these results by showing how omega-3 EPA and DHA supplementation decreased muscle soreness following eccentric contractions when compared with the control groups [38]. The trial examined the effects of EPA/DHA supplementation on muscle recovery in 16 men who were given supplements of 0.60 g/day mg of EPA and 0.26 g/day of DHA daily eight weeks prior to observed eccentric biceps contractions. The authors found that EPA/DHA-supplemented participants retained significantly higher torque and range of motion post-exercise compared with the placebo. Additionally, the placebo group experienced significantly higher muscle soreness compared with the supplemented group. Another study tested the effects of EPA/DHA supplementation on endurance athletes. Fifteen male endurance athletes were subjected to EPA/DHA or placebo supplementation over the course of ten weeks [56]. Test subjects were given gel packets containing 2.1 g/day of DHA and 0.24 g/day of EPA. The subjects then performed eccentric-induced muscle damage exercises. The authors of this study found that the EPA/DHA-supplemented group reported lower pain values relative to the placebo. While there is a considerable body of research that indicates that omega-3 PUFA supplementation alleviates muscle soreness, there are numerous studies that have found that omega-3 supplementation has no effect on muscle soreness. A recent study sought to verify whether omega-3 supplementation accelerated muscle recovery in 30 healthy women [57]. Participants were provided with either 3.2 g/day of omega-3 fish oil or a placebo for one week prior to undergoing resistance exercise training on a knee extensor machine. The authors found no significant difference in torque or muscle soreness between the fish oil-supplemented and placebo groups. While more research needs to be done to better understand the relationship between omega-3 supplementation and human health, the majority of studies indicate that omega-3 PUFAs aid in facilitating muscle recovery and decreasing soreness.

5.2. Inflammatory Processes

Rigorous exercise is known to increase chronic inflammation and oxidative stress, both of which have been associated with increased muscle weakness and atrophy [46]. Exercise-induced damage to muscle fibers causes inflammation, resulting in loss of strength and limited range of motion [58]. Oxidative stress is caused when reactive oxygen species (ROS) are overproduced due to increased oxygen uptake and heightened metabolic rates within the active myocytes. These ROS can attack biological macromolecules, leading to tissue damage and inflammation [59]. Omega-3 PUFAs have been linked to decreased levels of post-exercise biomarkers for inflammation and oxidative stress in the muscles. Omega-3 fatty acids reduce the production of inflammatory signaling molecules and downregulate the transcription of inflammatory cytokines and adhesion molecules, leading to a decrease in overall inflammation within the muscle tissues [58]. Several studies have measured the effect of omega-3 supplementation on inflammatory biomarkers. Gray et al. investigated the effect of fish oil supplementation on exercise-induced biomarkers for oxidative stress. The study separated 20

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male participants into fish oil-supplemented and placebo groups and observed blood biomarker levels post-exercise across six weeks. They found that fish oil supplementation significantly reduced the blood levels of thiobarbituric acid reactive substances and hydrogen peroxide-induced DNA damage, both biomarkers of oxidative stress [60]. A second study sought to examine the effect of EPA/DHA supplementation on oxidative stress by utilizing 14 exercise-trained men, subjecting them to six weeks of either EPA/DHA or placebo supplementation followed by an acute exercise session. Subjects were given doses of 2.2 g/day of EPA and 2.0 g/day of DHA administered in gel capsules morning and evening. Placebo participants were given identical capsules without EPA/DHA. The study found that EPA/DHA supplementation significantly lowered the levels of inflammatory biomarkers compared with the placebo [61].

However, not all the research done on the relationship between omega-3 PUFA supplementation has shown a decrease in inflammation or oxidative stress. In one study seeking to verify whether omega-3 EPA/DHA supplementation lowers inflammatory cytokine biomarkers in older men, 23 participants were chosen to undergo 12 weeks of 3.0 g/day of EPA/DHA or placebo supplementation prior to whole-body resistance training [22]. In this study, the authors determined that no significant change in inflammatory cytokines was identified in the EPA/DHA-supplemented group compared to the control. While further research is required in order to better understand how omega-3 PUFAs interact with inflammatory signaling in muscle cells, many recent studies suggest that omega-3 PUFA supplementation does have an effect on inflammation. Taken together, this research supports that omega-3 PUFA supplementation is correlated to a decrease in post-exercise inflammation and oxidative stress in skeletal muscles.

6. Conclusion

Omega-3 PUFAs have shown potential in promoting muscle growth, preventing sarcopenia, attenuating muscle atrophy, and enhancing muscle recovery after exercise-induced damage. The anti-inflammatory properties of omega-3 PUFAs and their ability to promote muscle protein synthesis are key mechanisms underlying these benefits. While further research is needed to fully elucidate the effects of omega-3 PUFAs on muscle health, current evidence suggests that omega-3 supplementation could be a valuable strategy for improving muscle mass and function, particularly in older adults and individuals at risk of muscle wasting.

Moreover, the implications of omega-3 PUFAs extend beyond just muscle health, impacting overall physical performance and quality of life. The ability to enhance muscle strength and endurance can contribute to improved mobility and reduced risk of falls in the elderly, thereby fostering greater independence and reducing healthcare costs associated with age-related physical decline. For athletes and physically active individuals, omega-3 supplementation could mean faster recovery times, reduced muscle soreness, and enhanced performance, making it a valuable addition to their dietary regimen.

In light of the growing body of evidence supporting the benefits of omega-3 PUFAs, integrating these fatty acids into public health recommendations and dietary guidelines could be beneficial. Considering their natural occurrence in foods such as fatty fish, flaxseeds, and walnuts, as well as their availability in supplement form, omega-3 PUFAs are accessible and can be incorporated into a variety of dietary patterns.

Future research should aim to determine the optimal dosages and forms of omega-3 supplementation for different populations and conditions, as well as to explore the long-term effects and safety of high-dose omega-3 intake. Additionally, studies should investigate the synergistic effects of omega-3 PUFAs with other nutrients and interventions, such as resistance training and protein supplementation, to develop comprehensive strategies for muscle health maintenance and improvement.

Overall, the promising role of omega-3 PUFAs in muscle health underscores the importance of these nutrients in our diet. By continuing to explore and understand their multifaceted benefits, we can better harness their potential to enhance muscle growth, prevent muscle loss, and improve recovery, ultimately contributing to healthier aging and better physical performance across the lifespan.

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