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## Isometric training and long-term adaptations; effects of muscle length, intensity and intent: A systematic review

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## ABSTRACT

Isometric training is used in the rehabilitation and physical preparation of athletes, special populations and the general public. However, little consensus exists regarding training guidelines for a variety of desired outcomes. Understanding the adaptive response to specific loading parameters would be of benefit to practitioners. The objective of this systematic review, therefore, was to detail the medium to long-term adaptations of different types of isometric training on morphological, neurological and performance variables. Exploration of the relevant subject matter was performed through MEDLINE, PubMed, SPORTDiscus and CINAHL databases. English, full-text, peer-reviewed journal articles and unpublished doctoral dissertations investigating medium to long-term ( $\geq 3$  weeks) adaptations to isometric training in humans were identified. These studies were evaluated further for methodological quality. Twenty-three research outputs were reviewed. Isometric training at longer muscle lengths (0.86-1.69%/week, ES = 0.03-0.09/week) produced greater muscular hypertrophy when compared to equal volumes of shorter muscle length training (0.08-0.83%/week, ES = -0.003-0.07/week). Ballistic intent resulted in greater neuromuscular activation (1.04-10.5%/week, ES = 0.02-0.31/week vs. 1.64-5.53%/week, ES = 0.03-0.20/week) and rapid force production (1.2-13.4%/week, ES = 0.05-0.61/week vs. 1.01-8.13%/week, ES = 0.06-0.22/week). Substantial improvements in muscular hypertrophy and maximal force production were reported regardless of training intensity. High-intensity ( $\geq 70\%$ ) contractions are required for improving tendon structure and function. Additionally, long muscle length training results in greater transference to dynamic performance. Despite relatively few studies meeting the inclusion criteria, this review provides practitioners with insight into which isometric training variables (e.g. joint angle, intensity, intent) to manipulate to achieve desired morphological and neuromuscular adaptations.

**Keywords:** Eccentric, fascicle, force, mechanical loading, muscle, tendon, stiffness, strength

## 1. INTRODUCTION

Resistance training is widely utilized as a component of physical preparation for populations ranging from elite strength and power athletes to injured members of the general public.<sup>1</sup> Commonly documented resistance training adaptations include increased muscle mass,<sup>2</sup> tendon quality,<sup>3-5</sup> strength, power, and range of motion,<sup>6</sup> delaying muscular fatigue,<sup>7,8</sup> and improving voluntary activation.<sup>9</sup> Dynamic movements incorporating the stretch-shortening cycle (SSC) comprise the overwhelming majority of resistance training programs.<sup>10</sup> However, isolated concentric, eccentric and isometric contractions have specific advantages when improving musculoskeletal properties and neuromuscular function,<sup>11-13</sup> and are increasing in popularity.<sup>14</sup> Isometric contractions (where the muscle-tendon unit remains at a constant length) and their role as a training option provide the focus of this paper.

Training with isometric contractions has been purported to have several advantages. First, isometric training allows for a tightly controlled application of force within pain-free joint angles in rehabilitative settings.<sup>15,16</sup> Second, isometric training provides a means to induce force overload as maximal isometric force is greater than that of concentric contractions.<sup>17</sup> Third, a practitioner who understands the physical demands of a sport may be able to utilize isometric training to focus on specific weak points in a range of motion that can positively transfer to performance<sup>18</sup> and injury prevention.<sup>19</sup> Isometric contractions can also be used to provide an acute analgesic effect and allow for pain-free dynamic loading<sup>20,21</sup> by altering excitatory and inhibitory functions in the corticomotor pathways.<sup>22</sup> Additionally, isometric contractions are a highly reliable means of assessing and tracking changes in force

production.<sup>23-25</sup> However, the ability of isometric assessments to predict dynamic performance is questionable,<sup>23-25</sup> despite multi-joint appraisals showing promise.<sup>26-29</sup>

Isometric training can elicit changes in physiological qualities including muscle architecture,<sup>30</sup> tendon stiffness and health,<sup>21,31</sup> joint angle-specific torque,<sup>31-33</sup> and metabolic functions.<sup>34</sup> As with any mode of resistance training, several variables can be manipulated to alter the stimulus. The most common isometric training variations include altering joint angles<sup>30-33,35-40</sup> and contraction intensity or duration.<sup>34,39,41-47</sup> Less frequently researched variations include contraction intent (eg. ramp vs. ballistic)<sup>43,47,48</sup> and incorporating special methods such as blood flow restriction,<sup>49,50</sup> vibration,<sup>51,52</sup> and electrical stimulation.<sup>53</sup>

Additionally, emerging research has demonstrated unique neuromuscular characteristics between “pushing” (i.e. exerting force against an immovable object) and “holding” (i.e. maintaining a joint position while resisting an external force) isometric contractions.<sup>54-60</sup>

Understanding the loading parameters that achieve a desired adaptive response in muscle and tendon would be of benefit to practitioners’. Therefore, the purpose of this review was to systematically evaluate research directly comparing the outcomes of isometric training variations and to provide training guidelines for a variety of desired outcomes.

## 2. METHODS

The systematic review conformed to the “Preferred Reporting Items for Systematic Reviews and Meta-Analyses” (PRISMA) guidelines.<sup>61</sup> Therefore, no Institutional Review Board approval was necessary.

### 2.1. Literature search methodology

An electronic search was conducted utilizing MEDLINE, SPORTDiscus, PubMed and CINAHL databases from inception to March 2018. Key terms were searched for within the article title, abstract, and keywords using conjunctions 'OR' and 'AND' with truncation '\*.' Combinations of the following Boolean phrases comprised the search terms: (Isometric train\*) AND (strength\* OR stiff\*); (Isometric train\*) AND (muscle\* OR tendon\*); (Isometric train\*) AND (session\* OR week\*).

### 2.2. Inclusion and exclusion criteria

Studies were included in the review based on the following criteria: 1) full text available in English; 2) peer-reviewed journal publications or doctoral dissertations; and, 3) the study compared two or more variations of isometric training. Studies were excluded if they; 1) were conference papers/posters/presentations; 2) focused on small joints or muscles such as fingers or toes; 3) primary dependent variables were related to cardiovascular health; 4) non-human subjects; 5) in-vitro; 6) the intervention period was less than three weeks in duration, 7) included variables such as blood restriction, vibration or electrical stimulation.

Search strategy and inclusion/exclusion results are summarized in Figure 1.

### 2.3. Quality assessment

Studies that met the inclusion criteria were assessed to determine their quality based on established scales utilized in the fields of sport and exercise science, kinesiology, health care and rehabilitation. Adapted from a systematic review by Brughelli et al.<sup>62</sup>, the scale developed for the current review is illustrated in Supplementary file 1. Ten items were scored as zero (clearly no), one (maybe), or two (clearly yes) based on this scoring rubric.<sup>62</sup>

Therefore, each study received a quality score ranging from zero to 20. Two researchers

completed the quality assessments of each paper with a third researcher settling any discrepancies in scoring.

#### 2.4. Statistical analysis

Percent change and Cohen's *d* effect sizes (ES) were calculated wherever possible to indicate the magnitude of the practical effect. Effect sizes were averaged across the length of an intervention where applicable. As recommended by Rhea,<sup>63</sup> effect sizes were interpreted as: trivial < 0.35, small = 0.35-0.80, medium = 0.80-1.50 and large > 1.5 for recreationally active participants.<sup>63</sup> Where possible, data was pooled and average ES change and % change (pre-post) per week were calculated. All reported ES and percentage changes are pre-post within-group, unless otherwise stated.

### 3. RESULTS

A total of 26 studies with a mean quality score of 14.3/20 (range = 10-18) met the inclusion criteria for the review (Supplementary file 2). A total of 713 participants (463 male, 250 female) were recruited with an average sample size of  $27.4 \pm 28.1$  (4-120). Of the accepted investigations, the mean age of the reported participants was  $24.3 \pm 3.3$  years (19.3-31.8); seven studies failed to report participant mean age. Most studies (16/26) recruited untrained participants, while the remainder (11/26) utilized "active" or "recreationally trained" participants. None of the accepted studies examined competitive athletes or well-trained participants. All 26 accepted investigations clearly stated independent and dependent variables, and 10 included a non-exercise control group. The mean length of intervention was  $8.4 \pm 3.6$  (range = 3-14) weeks, with an average of  $3.5 \pm 0.96$  (range = 2-7) sessions per week for an average of  $28.6 \pm 13.2$  (range = 15-56) total training sessions. Interventions were

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volume equated in 17/26 studies, while 10/26 studies included a non-exercise control group. Closed chain movements were only utilized in two studies, whereas 23/26 utilized single joint contractions.

Nine published journal articles and one unpublished doctoral dissertation examining the chronic (5-12 weeks) effects of isometric training at varying joint angles fulfilled the inclusion criteria (Table 1).<sup>30-33,35-38,40,64</sup> Of the ten included studies, eight centred on the knee extensors,<sup>30-33,35,38,40,64</sup> with two utilizing the elbow flexors.<sup>36,37</sup> Six published articles examining the effect of contraction intensity (Table 2) fulfilled the inclusion criteria.<sup>41,42,44-46,65</sup> Of these studies, three examined plantar flexors,<sup>41,42,65</sup> one examined knee extensors<sup>46</sup> while single studies examined the elbow flexors<sup>45</sup> and extensors, respectively<sup>44</sup>. Training variations outside of joint position or contraction intensity were also included. These variations include; 1) intent of contraction which included “progressive” vs “rapid”<sup>48,66</sup> and “explosive” vs “sustained”<sup>43,47,67</sup> contractions (Table 3); 2) total volume;<sup>39</sup> 3) contraction duration;<sup>13,34</sup> 4) rest period duration;<sup>68</sup> and 5) periodization schemes<sup>69</sup> (Table 4).

When synthesising statistically significant findings, measures of muscular size increased in nine studies (5-19.7%, ES = 0.19-1.23) by 0.84%/week and 0.043 ES/week.<sup>13,30-32,34,43,44,67,69</sup> Maximal isometric force significantly increased in 14 studies (8-60.3%, ES = 0.34-3.26) by 4.34%/week and 0.20 ES/week.<sup>32,35,37,38,40,43,44,46-48,64-67</sup> The comparison between joint angle and hypertrophic adaptation (n = 3 studies) revealed that training with joint angles  $\leq 70^\circ$  ( $46 \pm 6.9^\circ$ ) improved muscle size by an average of  $0.47 \pm 0.48\%$ /week and  $0.032 \pm 0.037$  ES/week, compared to  $1.16 \pm 0.46\%$ /week and  $0.067 \pm 0.032$  ES/week when training at  $> 70^\circ$  of flexion (Figure 2).<sup>30-32</sup> When comparing the nine studies that reported

training joint angle and hypertrophic adaptations, training with joint angles  $\leq 70^\circ$  ( $59.8 \pm 11.1^\circ$ ) improved muscle size by an average of  $0.61 \pm 0.42\%/week$  and  $0.045 \pm 0.034$  ES/week, compared to  $0.88 \pm 0.8\%/week$  and  $0.046 \pm 0.027$  ES/week when training at  $> 70^\circ$  ( $88.6 \pm 6^\circ$ ) of flexion (Supplementary file 3).<sup>13,30-32,34,43,44,67,69</sup> The comparative effects of training intensity on muscular hypertrophy were that intensities  $\leq 70\%$  ( $68.9 \pm 3.3\%$ ) of MVIC improved muscle size by  $0.77 \pm 0.26\%/week$  and  $0.13 \pm 0.12$  ES/week, compared to  $0.70 \pm 0.55\%/week$  and  $0.13 \pm 0.21$  ES/week when training at  $> 70\%$  ( $85.3 \pm 12\%$ ) of MVIC (Figure 3).<sup>13,30-32,34,43,44,67,69</sup> The comparisons of training intensity and improvements in isometric force (n = 3 studies) found that training at  $\leq 70\%$  ( $41.3 \pm 16.5\%$ ) of MVIC improved muscle size by  $6.8 \pm 3\%/week$  and  $0.32 \pm 0.13$  ES/week, compared to  $8.9 \pm 5.5\%/week$  and  $0.36 \pm 0.11$  ES/week when training at  $> 70\%$  ( $100 \pm 0\%$ ) of MVIC (Figure 4).<sup>44,46,65</sup> The joint angle-isometric force comparison (n=?) showed that training at  $\leq 70^\circ$  ( $42.8 \pm 16.4^\circ$ ) resulted in MVIC improvements of  $4 \pm 2.1\%/week$  and  $0.15 \pm 0.1$  ES/week, compared to  $3.4 \pm 4.2\%/week$  and  $0.15 \pm 0.17$  ES/week when training at  $> 70^\circ$  ( $101.8 \pm 24.2^\circ$ ) of flexion (Supplementary file 4).<sup>31,32,35,37,38,40,64</sup>

## 4. DISCUSSION

### 4.1. Morphological adaptations

Adaptations to the physical structure of tissues can be caused by several factors, including mechanical, metabolic and hormonal factors, and often results in altered function.

The morphology of the musculoskeletal system is of relevance to this review and provides the focus for subsequent discussion.



#### 4.1.1. *Muscle volume*

While most methods of progressive resistance training can result in increased muscular size, it is important to understand how to optimally alter variables including intensity, frequency, and duration of each training method for maximal efficiency. Isometric resistance training has been demonstrated to induce significant hypertrophy.<sup>13,30-32,34,39,43,44</sup>

When comparing adaptations in muscle volume between isometric training variations several patterns emerged, conforming to accepted dynamic training principles. Of the studies comparing isometric training at differing joint angles (Table 1), only three evaluated muscle volume or thickness.<sup>30-32</sup> All three studies found that isometric training at long muscle lengths (LML) was superior to equal volumes of training at short muscle lengths (SML) for increasing muscle size.<sup>30-32</sup> These findings are not surprising as a large portion of the existing literature has demonstrated that dynamic training through a large range of motion is beneficial when hypertrophy is desired.<sup>70-72</sup> Additionally, contractions at LML tend to produce higher quantities of muscle damage, likely by altering the joint moment arm and increasing mechanical tension when compared to a SML.<sup>73</sup> Contractions at LML also result in greater blood flow occlusion, rates of oxygen consumption, and metabolite build-up when compared to SML contractions.<sup>49</sup> These metabolic factors are well established to contribute to muscular hypertrophy.<sup>74,75</sup>

While volume equated isometric training leads to greater improvements in hypertrophy when performed at long muscle lengths (LML),<sup>30,32,33</sup> the magnitude of hypertrophy was not significantly different in any of the seven included studies investigating/reporting training intensity.<sup>13,30-32,34,43,44</sup> Interestingly, the pooled data of

included study outcomes suggests that training intensity has a small effect on hypertrophy, and explains little of the variation in hypertrophic adaptation (Figure 3). For example, Kubo et al.<sup>13</sup> compared the effects of load equated isometric contractions held for short (~1 s) or long (20 s) periods of time. While both long and short duration contractions led to small, but significant increases muscle thickness, there was little difference ( $p > 0.05$ ) between groups (7.6%, ES = 0.38,  $p = 0.023$  vs. 7.4%, ES = 0.36,  $p = 0.018$ ).<sup>13</sup> Similarly, Kanehisa et al.<sup>44</sup> employed ten-weeks of volume equated isometric training at either low (60%) or high (100%) intensity. While both low and high-intensity training programs significantly increased triceps brachii hypertrophy, there was no statistical between-group difference ( $p = 0.061$ ) in anatomical cross-sectional area (low: 12.1%, ES = 1.72 vs. high: 17.1%, ES = 1.65).<sup>44</sup> However, high intensity training had a greater effect on muscle volume than the lower intensity (12.4%, ES = 0.28 versus 5.3%, ES = 0.26;  $p = 0.039$ ) despite nearly identical effect sizes.<sup>44</sup> These findings are in close agreement with recent studies and meta-analyses that concluded that hypertrophic adaptations are similar if total load is equated and training intensity is greater than 20% of maximal voluntary contraction.<sup>76,77</sup>

When the training volume is not equated between groups, it seems higher volumes are better for inducing muscular hypertrophy, regardless of contraction intensity. Meyers<sup>39</sup> compared low (3 x 6-s MVIC) and high (20 x 6-s MVIC) volume isometric training of the elbow flexors. Following the six-week intervention, the high-volume training program resulted in significantly greater improvements in muscle girth compared to the low volume group ( $p < 0.05$ ). Similarly, Balshaw et al.<sup>43</sup> and Massey et al.<sup>67</sup> compared “maximal strength” (40 x 3-s contractions, 75% of MVIC) and “explosive” (40 x 1-s contractions, 80% of MVIC) isometric training. Following the 12-week interventions, the “maximal strength” training groups experienced significant improvements in quadriceps muscle volume (8.1%,

ES = 0.50,  $p = 0.001$ ) whereas the “explosive” training groups (2.6%, ES = 0.17-0.26,  $p = 0.195$ -0.247) did not.<sup>43</sup> Furthermore, the difference between groups was statistically significant ( $p < 0.05$ ).<sup>43,67</sup> Interestingly, Schott, McCully and Rutherford<sup>34</sup> found that long duration (4 x 30-second MVIC) contractions resulted in greater hypertrophic adaptations when compared to short (4 sets x 10 x 3-second MVIC) duration contractions despite total time-under-tension being equated between groups. Following 14-weeks, the long duration contraction group significantly ( $p = 0.022$ ) improved vastus lateralis anatomical cross-sectional area at the proximal (10.1%) and distal (11.1%) portion of the femur, whereas no significant hypertrophic adaptations were observed in the short duration group ( $p > 0.05$ ).<sup>34</sup> Schott, McCully and Rutherford’s<sup>34</sup> findings are somewhat surprising as both groups underwent the same time-under-tension. However, sustained contractions are known to restrict blood flow, reduce muscle oxygen saturation and increase metabolite concentrations in the muscle<sup>78,79</sup> stimulating hypertrophy via multiple local and systemic mechanisms.<sup>74,75</sup> Additionally, muscle contractions at LML consume more oxygen,<sup>49</sup> which may in-part explain the advantage of LML training when muscular hypertrophy is the primary goal.

#### 4.1.2. *Muscle architecture*

Unlike muscle volume, which is highly dependent on total training volume, there are demonstrable differences between contraction type and alteration in fascicle length and pennation angle.<sup>80</sup> To date, very few studies have compared the effect of isometric resistance training variations on muscle architecture; of those that have, results are equivocal. Noorkoiv, Nosaka and Blazeovich<sup>32</sup> compared isometric training at SML ( $38.1 \pm 3.7^\circ$  knee flexion) and LML ( $87.5 \pm 6^\circ$  knee flexion). Interestingly, the vastus lateralis fascicle length at the mid-portion of the femur significantly increased following SML (5.6%, ES = 0.63,  $p = 0.01$ ), but not LML (3.8%, ES = 0.34,  $p = 0.20$ ) training.<sup>32</sup> Conversely, LML (5.8%, ES = 0.33,  $p =$

0.02) significantly ( $p = 0.01$ ) outperformed SML training (-1.1%, ES = 0.04,  $p > 0.05$ ) for increasing distal fascicle length of the same muscle.<sup>32</sup> Furthermore, LML training resulted in greater ( $p < 0.01$ ) physiological cross-sectional areas in three of the four quadriceps heads, whereas the SML training, did not ( $p > 0.05$ ).<sup>32</sup> Only one other isometric training comparison study reported meaningful shifts in muscle architecture; found that vastus lateralis pennation angle increased following LML (10.6%, ES = 0.45,  $p = 0.038$ ), but not SML training (6.5%, ES = 0.46,  $p = 0.076$ ).<sup>30</sup> However, Alegre et al.<sup>30</sup> only measured the vastus lateralis pennation angle at the midpoint of the femur and potentially missed out on possible adaptations at the distal portion of the muscle.

#### 4.1.3. *Tendon morphology*

The primary function of the tendon is to transfer forces between bone and muscle, facilitating joint motion.<sup>5</sup> Although originally assumed to be inert, tendinous structures can experience adaptations and are capable of significant architectural adaptations from habitual loading and injury.<sup>3-5,81-83</sup> Injured tendons tend to be less stiff, despite increased thickness<sup>84</sup> due to a shift in viscoelastic properties.<sup>5</sup> Additionally, tendinopathy negatively affects tendon structure, leading to increased vascularization and overall thickness.<sup>5,84</sup> Although long-term alteration in tendon morphology is minimal in healthy, mature human tissue,<sup>5</sup> tendons can increase in stiffness to optimize the time and magnitude of force transmission between muscle and bone.<sup>3,4,82</sup> Conversely, healthy increases in tendon thickness and stiffness in response to exercise, have been found to be region specific and may have rehabilitative, pre-habilitative and performance benefits.<sup>3,4,20,81,82</sup> For instance, heavy (resistance) training can lead to an increase in maximal muscular force and rate of force development by increasing tendon stiffness, thus reducing the electromechanical delay.<sup>5,83,85</sup> Additionally, increased tendon stiffness through chronic loading can be due to increased tendon CSA without

alterations in viscoelastic properties, potentially improving safety when performing ballistic movements.<sup>5</sup> While widely used in rehabilitation settings, there is a general lack of information regarding what isometric training variables are important for triggering specific tendonous adaptations.

Of the studies included in this review, only six directly assessed tendon structure or function. Two studies compared contraction intensity,<sup>41,42</sup> with others examining the effects of contraction length,<sup>13</sup> intent,<sup>67</sup> rest periods,<sup>68</sup> and joint angle.<sup>31</sup> Arampatzis et al.<sup>41,42</sup> compared 14-week training programs consisting of volume equated isometric plantar flexion at low (~55%) or high (~90%) intensities. Both investigations found increased Achilles tendon CSA and stiffness following high (17.1-36%, ES = 0.82-1.57,  $p < 0.05$ ), but not low (-5.2-7.9%, ES = 0.26-0.37,  $p > 0.05$ ) intensity training.<sup>41,42</sup> Furthermore, tendon elongation under stress (an indication of elasticity) increased following low (14.0-16.1%, ES = 0.56-0.84,  $p > 0.05$ ), but not high (-1.4-3.9%, ES = 0.06-0.20,  $p > 0.05$ ) intensity training.<sup>41,42</sup> Additionally, the included studies only compared isometric training at ~55 and 90% of MVIC which leaves a large range of potential intensities. However, previous interventions have reported large increases (17.5-61.6%, ES = 0.57-4.9,  $p < 0.05$ ) in tendon stiffness following training between 70-100% of MVIC.<sup>11,13,85</sup> Therefore, it might be that a minimum intensity of ~70% MVIC is required to induce meaningful changes in tendon thickness and stiffness.

While only a single study has examined the effect of isometric training at different muscle lengths on tendon adaptation,<sup>31</sup> the results tend to support a paradigm of LML training being superior to SML training. Kubo et al.<sup>31</sup> trained the knee extensors at either 50° or 90° of flexion and observed a significantly greater increases in tendon stiffness ( $p = 0.021$ )

following LML (50.9%, ES = 1.22,  $p = 0.014$ ), when compared to SML training (6.7%, ES = 0.26,  $p = 0.181$ ). Similarly, distal tendon and deep aponeurosis elongation decreased following LML training (-14%, ES = 0.62,  $p = 0.034$ ), whereas the SML group experiences a trivial increase (3.9%, ES = 0.15,  $p > 0.05$ ). When comparing isometric contraction duration and tendon adaptations, only a single study exists.<sup>13</sup> While both long (57.3%, ES = 1.38,  $p = 0.003$ ) and short (17.5%, ES = 0.57,  $p = 0.217$ ) contraction durations increased tendon stiffness, a significant between-group difference was reported ( $p = 0.045$ ).<sup>13</sup> Additionally, no significant differences in tendon elongation were present in either long (-2.2%, ES = 0.19,  $p > 0.05$ ) or short (4.1%, ES = 0.29,  $p > 0.05$ ) contraction duration groups. Similarly, calculated elastic energy absorption increased in both long (12%, ES = 0.58,  $p = 0.007$ ) and short (25.7%, ES = 1.85,  $p = 0.002$ ) duration groups with no significant difference between groups ( $p = 0.056$ ) despite large differences in percent change and effects sizes along with a relatively low  $p$ -value. While the total time-under-tension was equalized between groups, the one-second duration of the short contraction group meant that a larger relative proportion of each effort would be spent building isometric force. Therefore the maximal-force time-under-tension was not equalised.<sup>13</sup> Similar to muscle tissue, tendon adaptations are responsive to chronic changes in total mechanical load,<sup>3,86,87</sup> therefore, the potentially greater load in the long contraction group could explain the discrepancy in tendonous adaptations.

Massey et al.<sup>67</sup> were the only researchers comparing contraction intent on morphological tendon adaptations. Both “maximal strength training” and “explosive strength training” produced significant improvements in vastus lateralis aponeurosis area (5.9%, ES = 0.34 vs. 4.4%, ES = 0.38), Young’s modulus (14.4%, ES = 0.60 vs. 21.1%, ES = 1.13) and tendon stiffness (14.3%, ES = 0.79 vs. 19.9%, ES = 0.95).<sup>67</sup> However, only the “explosive strength training” group experienced significant increases in tendon-aponeurosis complex

elongation (16%, ES = 1.0 vs. -2.96, ES = 0.10) and decreased tendon CSA (-2.8%, ES = 0.31 vs. 0.41%, ES = 0.03), tendon elongation (-11%, ES = 0.75 vs. -4.95%, ES = 0.27) and tendon strain (-11.8%, ES = 0.56 vs. -4.17, ES = 0.19).<sup>67</sup> Therefore, intent and rate of contraction appear to be an important training consideration. Lastly, Waugh et al.<sup>68</sup> compared load equated isometric plantar flexions with intra-contraction rest periods of three, or 10 seconds. While there were differences ( $p > 0.05$ ) in type-I and type-II collagen (factors in fibre re-organization),<sup>88,89</sup> there were no between-group discrepancies ( $p > 0.05$ ) in any other dependent variables following the 14-week intervention.<sup>68</sup> These data support a paradigm of a threshold intensity for mechanical loading to achieve tendon adaptations.<sup>86,87</sup>

#### 4.2. Neurological adaptations

Of the 23 studies included in this review, 12 directly measured neural function.<sup>13,30-32,37,38,43,47,48,65,66,68</sup> Of these 12 studies, it is notable that one did not report any neurological data in their results,<sup>68</sup> while two reported no significant changes following training, regardless of the condition.<sup>13,65</sup> When examining EMG amplitude assessed through electromyography (EMG), a clear trend existed between the studies comparing isometric training at different muscle lengths. Electromyographic amplitude tends to increase by larger magnitudes and over a larger range of joint angles following LML training, compared to training at SML. For example, Bandy and Hanten<sup>38</sup> examined isometric knee extension training at SML (30°), medium muscle length (MML; 60°) and LML (90°), assessing EMG amplitude at seven joint angles from 15°-105° of flexion. Medium to large (ES = 0.74-2.28) improvements at six joint angles were observed following LML training, whereas MML and SML training only improved EMG activity at five (ES = 0.36-2.26), and four (ES = 0.87-1.65) of the assessed joint angles, respectively.<sup>38</sup> Similarly, Kubo et al.<sup>31</sup> observed larger increases in EMG activity at all measured angles following LML (7-8.8%, ES = 0.45-0.72) compared to SML (3.1-

7.5%, ES = 0.25-0.44) training. Conversely, Alegre et al.<sup>30</sup> reported an increase in EMG amplitude in favour of the SML training group, the only investigation to do so. Although the magnitude of increases in EMG amplitude were medium-large, the changes were limited to 50-60° (ES = 0.77,  $p = 0.205$ ) and 60-70° (ES = 1.0,  $p = 0.36$ ) of knee flexion during isokinetic knee extensions.<sup>30</sup> These findings are consistent with the findings of other investigations in that alterations in EMG amplitude are most specific at shorter muscle lengths.<sup>37,71,72</sup>

All four studies comparing the effects of isometric training with different contraction intents (ballistic vs. ramp) assessed neurological and neuromuscular adaptations via EMG and peripheral nerve stimulation interpolated twitch.<sup>43,47,48,66</sup> As expected, adaptations were specific to the intent utilized in training. For example, Balshaw et al.<sup>43</sup> examined the effects of 12 weeks of “maximal strength training” (1-s build to ~75% of MVIC and maintain for 3-s), with “explosive strength training” (rapid build to  $\geq 90\%$  of MVIC and maintain for 1-s). The improvements in EMG amplitude at MVIC were larger (ES = 0.36,  $p = 0.370$ ) following “maximal strength training” (27.8%, ES = 0.67,  $p < 0.001$ ) compared to “explosive strength training” (19.1%, ES = 0.44,  $p = 0.099$ ). Conversely, “explosive strength training” (31.3%, ES = 0.67,  $p = 0.003$ ) increased EMG activity to a greater ( $p < 0.001$ ) degree during the 0-100 ms and 0-150 ms period of muscle contraction compared to “maximal strength training” (14.3%, ES = 0.36,  $p = 0.009$ ).<sup>43</sup> Additionally, only the rapid contraction group significantly increased EMG amplitude in the first 100 ms of muscle contraction (12.5%, ES = 0.26,  $p = 0.048$ ).<sup>43</sup> Similarly, previous investigations examining contraction intent found greater improvements in EMG amplitude during MVIC with MST (1.28-7%/week, ES = 0.06-0.33/week) when compared to EST (0.68-1.31%/week, ES = 0.18-0.25/week).<sup>47,48,66</sup> Furthermore, participants training with a ballistic intent (1.04-10.5%/week, ES = 0.26-



0.31/week) achieved greater improvement in EMG amplitude during the initial 150 ms of maximal contraction when compared to MST (2.93-5.53%/week, ES = 0.03-0.07/week).<sup>43,47,48,66</sup> These findings support the principle of training specificity as only the groups who intended to produce force quickly, improved in that regard.

#### 4.3. Performance enhancement

Isometric training is commonly prescribed in rehabilitation settings, or early in physical preparation plans as a means to increase neuromuscular, musculoskeletal and proprioceptive function. It is thought that the aforementioned improvements will later transfer to dynamic performance once specific movement patterns are integrated into the physical preparation plan. Despite existing literature reporting benefits of isometric training on multi-joint dynamic performance,<sup>11,85,90</sup> none of the studies included in the current review included dynamic multi-joint assessments.

##### 4.3.1. *Isometric peak force*

Only four studies included in the present review directly compared MVIC production between groups training at different intensities.<sup>44-46,65</sup> Isometric peak force is considered a highly reliable measure, with a growing body of research reporting the validity of isometric assessments for assessing health and athletic performance.<sup>28,91</sup> While training specificity is a major factor in performance improvements, if MVIC force is the desired outcome there does not appear to be a clear advantage to training at high or low intensities (Figure 4). Szeto et al.<sup>46</sup> was the only study that reported statistically significant improvements in MVIC force in some, but not all training groups. Szeto et al.<sup>46</sup> had subjects train their knee extensors at 25%, 50% or 100% of MVIC. Following 15 sessions over three weeks, the group training at 25% did not experience statistically significant strength improvements despite medium effect sizes

(22.3%, ES = 0.61,  $p = 0.085$ ).<sup>46</sup> Conversely, large and statistically significant improvements were observed when training at 50% (31.3%, ES = 1.14,  $p = 0.002$ ) and 100% (45.7%, ES = 1.44,  $p = 0.013$ ) of MVIC.<sup>46</sup> However, time-under-tension, not total load, was equalized between groups, meaning that the 50% training group produced twice as much total force as the 25% group. While no data about fatigue is presented, it could be hypothesized that the group training with maximal effort underwent significantly greater loading than the other groups.<sup>46</sup> Additionally, the inclusion of a perceived effort or fatigue scale may have been valuable.

A clear pattern can be observed when comparing maximal force production following training at different muscle lengths. Despite LML resulting in greater hypertrophic adaptations, there is no difference in maximal force production at the trained joint angle between SML and LML interventions when analyzing the seven studies that directly compared joint angles (Supplementary file 4).<sup>31,32,35,37,38,40,64</sup> However, transfer to non-trained joint angles is much lower following SML training. For example, Bandy and Hanten,<sup>38</sup> Bogdanis et al.<sup>64</sup> Kubo et al.<sup>31</sup> and Thepaut-Mathieu, van Hoecke and Maton<sup>37</sup> all trained participants at different muscle lengths and measured MVIC at numerous joint angles pre- and post-training. Bandy and Hanten<sup>38</sup> observed significant ( $p < 0.05$ ) improvements at four, five and seven of the tested joint angles following SML, MML and LML respectively. Bogdanis et al.<sup>64</sup> reported increased MVIC at two of the assessed joint angles following SML training (22-57.4%, ES = 0.88-2.41), while the LML group improved in all six angles (~12.3%). Similarly, the SML group in Kubo et al.'s<sup>31</sup> investigation significantly ( $p < 0.05$ ) improved MVIC at five angles while the LML group experienced significantly improved force production at eight of the tested angles. Interestingly, Thepaut-Mathieu, Van Hoecke and Maton<sup>37</sup> found that their LML group significantly ( $p < 0.05$ ) improved at four angles,

compared to two and five angles in the SML and MML group respectively. These data suggest that LML and MML isometric resistance training is superior to SMLs when the aim is to improve force throughout a range of motion.

#### 4.3.2. *Length-tension*

The length-tension relationship, typically assessed by isometric or isokinetic contractions, is defined as the muscle length or joint angle at which peak force/torque is produced.<sup>92</sup> Many studies have demonstrated acute optimal angle/length shifts towards longer muscle lengths following concentric, isometric and eccentric exercise.<sup>73,93-98</sup> Additionally, eccentric resistance training and training over a larger range of motion are well established for increasing the optimal angle long-term.<sup>70,95</sup> It is plausible that the same relationship exists between muscle length and a shift in the optimal angle following isometric contractions. However, only a single study included in this review reported the angle of peak isokinetic torque,<sup>30</sup> while another examined optimal angle through an isometric leg-press.<sup>64</sup> Alegre et al.<sup>30</sup> observed a shift of 11° (14.6%, ES = 1.1,  $p = 0.002$ ) towards longer muscle lengths following eight weeks of training at LML, whereas the SML group experienced a shift of 5.3° (7.3%, ES = 0.91,  $p = 0.039$ ) in the opposite direction. Likewise, Bogdanis et al.<sup>64</sup> reported a decrease in optimal angle following SML training (-9.7%, ES = 1.77) while the optimal angle was maintained in the LML group. While length-tension curve shifted toward the angle of training in several other studies, none were significant or altered the angle at which maximal isometric force was produced.<sup>30</sup> While a very limited sample, the report of Alegre et al.<sup>30</sup> is unsurprising given that isometric exercise at LMLs is preferable to SMLs for acutely altering the length-tension relationship.<sup>99</sup> Finally, it should be noted that no included study reported any significant differences in isometric or isokinetic length-tension curves between groups training with different intensities, contraction intents or any other independent variable.

#### 4.3.3. *The rate of force development*

The rate of force development (RFD) is an important measurement in sports performance, as force application in many activities occurs over short time periods.<sup>14,100-102</sup> Therefore, while peak force is a valid and highly reliable means of broadly monitoring neuromuscular function, rapid force production characteristics are equally valuable and more specific to the execution of explosive tasks.<sup>2,100-103</sup> Unfortunately, only three training studies examining different contraction intents reported RFD variables.<sup>43,47,48</sup> Regardless, all three studies reported that isometric training with an “explosive” or “ballistic” intent was superior to ramping contractions for improving rapid force production.<sup>43,47,66</sup> These findings align with the previously discussed alterations in EMG amplitude between contraction intents. For example, Williams<sup>66</sup> compared the adaptations following ballistic or ramp isometric training. While the ramp group experienced larger, improvements in MVIC (ramp, 17.8-20%, ES = 1.56-1.95,  $p = 0.0008$  vs. ballistic, 15.7-18.9%, ES = 0.75-0.88,  $p = 0.0036$ ), only the ballistic training group significantly improved voluntary activation (31.6%, ES = 1.84,  $p = 0.0096$ ) and force at 150 ms (48.8%, ES = 1.29,  $p = 0.0074$ ).<sup>66</sup> Similar findings are reported by Balshaw et al.<sup>43</sup> and Tillin and Folland<sup>47</sup> where only the ballistic training groups significantly ( $p < 0.05$ ) improved force at 50 ms and 100 ms (Table 3). These findings are not surprising, as several researchers have reported increased rapid force and power production, driven heavily by neurological alterations.<sup>104-106</sup> Additionally, there is evidence to suggest that the intent of movement may be of similar value to actual external contraction velocity when improving RFD characteristics.<sup>107</sup>

#### 4.3.4. *Dynamic performance*

The transferability of isometric resistance training to dynamic performance is questionable, despite specific isometric assessments closely relating to sports performance.<sup>91</sup> Likewise, the degree of transference of isokinetic contraction to real-world movements has yet to be elucidated fully.<sup>24,26,27</sup> Regardless, isokinetic testing provides a valuable means of assessing dynamic performance. Five studies utilized isokinetic assessments with three comparing various trained joint angles,<sup>30,40,48</sup> and two studies comparing contraction intent<sup>48</sup> or length of contraction respectively.<sup>34</sup> Maffiuletti and Martin<sup>48</sup> reported similar improvements in eccentric torque at  $60^{\circ}\cdot\text{s}^{-1}$  and concentric torque at slow ( $60^{\circ}\cdot\text{s}^{-1}$ ) and faster ( $120^{\circ}\cdot\text{s}^{-1}$ ) angular velocities regardless of contraction intent. When comparing isometric training at different muscle lengths, Alegre et al.<sup>30</sup> and Noorkoiv et al.<sup>33</sup> observed significant ( $p < 0.05$ ) improvements after training at LML, but not SML in concentric torque at  $60^{\circ}\cdot\text{s}^{-1}$  and  $30^{\circ}\cdot\text{s}^{-1}$ ,  $60^{\circ}\cdot\text{s}^{-1}$ ,  $90^{\circ}\cdot\text{s}^{-1}$  and  $120^{\circ}\cdot\text{s}^{-1}$  respectively, despite no significant differences in MVIC improvements between groups. Conversely, Lindh<sup>40</sup> reported that neither SML or LML training groups improved isokinetic torque at  $180^{\circ}\cdot\text{s}^{-1}$  while both groups significantly ( $p < 0.01$ ) improved peak torque at  $30^{\circ}\cdot\text{s}^{-1}$ . Finally, Bogdanis et al.<sup>64</sup> observed similar improvements in one repetition maximum squat (9.6%, ES = 0.61 vs. 11.9%, ES = 0.64) and countermovement jump height (7.2%, ES = 0.66 vs. 8.4%, ES = 0.51) following SML and LML leg press training, respectively. One possible explanation for these findings is that the LML training groups in Alegre et al.<sup>30</sup> and Noorkoiv et al.'s<sup>33</sup> experienced larger hypertrophic adaptations than the corresponding SML participants. Unfortunately, neither Lindh<sup>40</sup> or Bogdanis et al.<sup>64</sup> assessed morphological adaptations, making further analysis difficult.

#### 4.4. Applications

While the direct transfer of isometric resistance training to dynamic movements is questionable, physiological adaptations such as increased muscle mass and improved tendon qualities are beneficial in a variety of contexts. There is a well-established relationship between muscle mass, strength and functional performance in a variety of activities and populations.<sup>108-110</sup> While it may require specific training in a movement to optimize neuromuscular performance,<sup>71,111</sup> it is clear that producing and maintaining muscle mass and strength should be a priority for athletes and special populations alike. For this reason, isometric contractions are regularly used in rehabilitation programs and during specific training phases where dynamic contractions may be contraindicated.

The long-held belief that isometric resistance training should occur at the most important angle present in a dynamic activity holds true<sup>112-115</sup> as the largest improvements in neuromuscular function occur at the trained angle.<sup>31,32,37,38,40</sup> However, large neurological discrepancies exist between isometric and dynamic movements<sup>25</sup> suggesting that static training may not be an effective strategy for directly improving sports performance and should be primarily employed to alter morphology. Therefore, isometric training should occur predominantly at relatively LMLs as there is a clear advantage for improving muscle volumes (Figure 2), and strength throughout a range of motion.<sup>30-33,37,38</sup> Additionally, large increases in tendon stiffness following LML have been reported, which would likely reduce electromechanical delay and therefore improve RFD.<sup>5,31,116</sup> Furthermore, LML isometric training may have beneficial effects on the length-tension relationship,<sup>30</sup> although greater evidence is needed to solidify optimal angle as a key variable in performance and injury prevention.<sup>92</sup> Similarly, architectural qualities of muscle may underpin the length-tension

relationships. However, Alegre et al.<sup>30</sup> observed no significant ( $p > 0.05$ ) shift in fascicle length regardless of training angle, while Noorkoiv et al.<sup>32</sup> reported conflicting findings depending on which quadriceps head was evaluated. Therefore, isometric resistance training, regardless of muscle length, appears unlikely to efficiently lengthen muscle fascicles.

Training intensity is a key variable prescribed in intelligently designed resistance training programs. Evidence suggests that high-intensity resistance training is superior for improving force production.<sup>45,76,117</sup> However, the studies cited in this review show a questionable relationship between intensity and force production adaptations (Figure 4).<sup>13,30-32,34,43,44,46,65</sup> Consistent with recent original research and meta-analyses, isometric training intensity does not appear to affect hypertrophic adaptations.<sup>76,77</sup> While the lack of relationship between contraction intensity and force production is somewhat surprising, previous literature has reported that submaximal intensities can produce similar strength improvements when taken to failure, or when the volume is equated between groups.<sup>77,118</sup> These findings suggest that isometric training intensity is not important when aiming to improve force production or alter muscle morphology. Therefore, increasing contraction durations,<sup>34</sup> increasing total volume, or shifting to longer muscle lengths<sup>30-32,38,40</sup> are likely more efficient means of progressing isometric resistance training if strength and muscle size are a priority. Conversely, high-intensity ( $\geq 70\%$  of MVIC) isometric contraction exclusively produced increased tendon thickness and stiffness.<sup>41,42</sup> As overly compliant tendons are often an issue in untrained and injured populations, progressively increasing intensity during isometric contractions may be a safe and efficient means of preparing tendinous tissue for future dynamic loading.<sup>12,82</sup> Additionally, sports requiring a high degree of reactive strength require relatively stiff tendinous structures to optimize performance.<sup>90,119,120</sup>

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Isometric training, like other modes of resistance exercise, should be executed in a way that most closely relates to the primary outcome goal. When muscular hypertrophy or maximal force production is the priority, the evidence demonstrates that there is little difference between contractions completed with a ballistic, or a gradual ramp to the prescribed intensity.<sup>43,47,48,66</sup> However, if rapid force production takes precedence, as it would in several sports, then isometric contractions should be performed as such.<sup>43,47,66</sup> Conversely, ballistic contractions may be contra-indicated or cause excessive pain in rehabilitative or special populations,<sup>20</sup> despite potential to provide unique morphological tendon adaptations.<sup>67</sup> Therefore, while ballistic contractions offer unique neuromuscular benefits, sustained contractions generally offer similar or greater morphological adaptations that are likely of interest to a wider variety of trainee.<sup>43,48,66</sup>

#### 4.5. Limitations and directions for future research

While trends, or lack thereof, are evident in many of the key independent variables discussed in the current review, several limitations exist. While the widely homogeneous populations inter, and intra-study allowed for simple analysis, none of the included studies utilized special populations such as patients with tendon disorders, high-performance athletes or experienced resistance trainees. Researchers and practitioners alike need to be cognizant of this limitation if wishing to generalize findings. Similarly, very few of the included studies examined the effect of isometric training on dynamic performance, and only one utilized closed-chain or functional performance tasks in their testing batteries. Finally, while 26 studies were included, the large variety of independent and dependent variables made extensive inter-study analysis difficult and hence definitive conclusions problematic.



While the limitations present are broad, several directions for interesting future research exist. Isometric resistance training is often utilized by strength and conditioning coaches early in a training plan with the intent of preparing muscle and tendon morphologies for future dynamic loading. However, to the authors' knowledge, no published studies have examined the effect of a preceding isometric training phase on dynamic or ballistic training periods despite a rise in popularity with this approach.<sup>14</sup> On a related note, a limited number of studies have examined isometric training with free-weights. Isometric contraction intensity does not play a large role in driving morphological or neuromuscular adaptations, and total volume is likely a more important variable. However, resistance training modes have specific load cut-off points for altering tissue or neural properties.<sup>1,10</sup> As such, future studies should aim to establish approximate weekly loading guidelines for a variety of populations, muscle groups and dependent variables. Another interesting direction is determining whether isometric training can improve dynamic muscular endurance. Unfortunately, only a single included study evaluated fatigue,<sup>65</sup> and no studies examined fatigue during dynamic or stretch-shortening cycle activities such as cycling or running.

Another avenue for research geared towards rehabilitative populations is a multivariate examination of contraction intensity and joint angles. Physical therapists often prescribe isometric training as a means to stimulate morphological adaptations and improve neuromuscular function while tightly maintaining a pain-free range of motion. Anecdotally, therapists often limit isometric contractions to moderate joint angles as the increased ligament strain and pressure synonymous with maximal contraction intensities at large degrees of joint flexion may cause unwanted pain and inhibition.<sup>15,16</sup> However, training at LML is superior to SML training for producing morphological and neuromuscular adaptations. Therefore, it would be fascinating to compare the effects of submaximal isometric training at LMLs with

maximal isometric training at SMLs. As previously mentioned, the body of literature examining the characteristics of “pushing”, “holding” and “quasi” isometric actions is growing.<sup>54-60,78</sup> However, there is a paucity of long-term experimental studies examining these isometric contraction subsets.

## 5. PERSPECTIVES

Despite a relatively limited quantity of studies to base conclusions upon, specificity of training applies to isometric resistance training as it does to traditional dynamic resistance training. Therefore, isometric training should be prescribed in line with the primary outcome goals. Training at LML and with sustained contractions have been found to be beneficial for improving muscle morphology, while high-intensity contractions (>70% MVC) are likely required to substantially improve tendon structure and function (e.g. tendon stiffness). Similarly, ballistic intent has been found to improve rapid force production even though movement velocity is zero. Finally, a greater number of studies, with a broader application of isometric training variations are needed to determine optimal applications for altering the morphology and improving dynamic performance in athletic, rehabilitative and special populations alike.

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Figure 1. Search strategy

Figure 2. Isometrically trained joint angle and hypertrophic adaptations ( $N = 3$ )

Figure 3. Isometric training intensity and hypertrophic adaptations (multiple comparison,  $N = 9$ )

Figure 4. Isometric training intensity and force production ( $N = 3$ )

Table 1. Joint angle

Study, year (quality)	Subjects	Intervention	Mechanical and neural adaptations ( $p < 0.05$ , $ES \geq 0.50$ )	Performance effect ( $p < 0.05$ , $ES \geq 0.50$ )
Alegre, Ferri-Morales, Rodriguez-Casares, & Aguado (2014) <sup>30</sup> (18/20)	Healthy, untrained university students  M = 22 F = 7  19.3 years	Isometric knee extension  SML = 50° LML = 90°  ~74% of MVIC  8 weeks, 2-3/week	SML: ↑VL thickness at 25% and 50% muscle length (5.2-6.1%, $ES = 0.23-0.24$ ) ↑isokinetic EMG at 60-70° ( $ES = 1.0$ ) and 50-60° ( $p = 0.21$ , $ES = 0.77$ )  LML: ↑VL thickness at 25%, 50%, and 75% muscle length (9-13.5%, $ES = 0.31-0.65$ ) ↑VL pennation angle (11.7%, $ES = 0.45$ )	SML: ↓Optimum angle (7.3%, $ES = 0.91$ )  LML: ↑Concentric torque at 60°·s <sup>-1</sup> (22.6%, $ES = 1.1$ ) ↑Optimum angle (14.6%, $ES = 1.38$ )
Bandy & Hanten (1993) <sup>38</sup> (18/20)	Healthy, untrained, university students  F = 107  23.9 years	Isometric knee extension  SML = 30° MML = 60° LML = 90°  100% of MVIC  8 weeks, 4/week	SML: ↑EMG at 15°, 30°, 45° and 60° vs. ↑EMG in control ( $ES = 0.87-1.65$ )  MML: ↑EMG at 15°, 30°, 45°, 60° and 70° vs. ↑EMG control ( $ES = 0.36-2.26$ )  LML: ↑EMG at 30°, 45°, 60°, 75°, 90°, and 105° vs. ↑EMG in control ( $ES = 0.74-2.28$ )	SML: ↑MVIC at 15°, 30°, 45° and 60° ( $ES = 0.88-1.94$ )  MML: ↑MVIC at 15°, 30°, 45°, 60° and 75° ( $ES = 1.01-2.25$ )  LML: ↑MVIC at 15°, 30°, 45°, 60°, 75°, 90°, and 105° ( $ES = 0.94-3.26$ )
Bogdanis et al., (2018) <sup>64</sup> (15/20)	Healthy, active university students  M = 15  21.5 ± 2.1 years	Isometric leg press (+ countermovement jumps)  SML = 35° of knee flexion  LML = 95° of knee flexion		SML: ↓Optimum angle (9.7%, $ES = 1.77$ ) ↑MVIC at 18° (22%, $ES = 0.88$ ) and 34° (57.4%, $ES = 2.41$ ) ↓RFD 0-200ms and 0-300ms at 80° (11.8-13.8%, $ES = 0.51-0.60$ ) ↑RFD 0-200ms and 0-300ms at 18° (40.7-

		100% of MVIC 6 weeks, 3/week		45.4%, ES = 1.2-1.52) and 34° (17.9-20.9%, ES = 0.62-0.77) ↑1RM squat (9.6%, ES = 0.61) ↑CMJ height (7.2%, ES = 0.66)  LML: ↑MVIC (main time effect: $p = 0.028$ ) at all joint angles (18-98°) (~12.3%) *↑RFD 0-300ms at 34° (14.4%, ES = 0.52) ↑1RM squat (11.9%, ES = 0.64) ↑CMJ height (8.4%, ES = 0.51)
Kubo et al., (2006) <sup>31</sup> (11/20)	Healthy university students  M = 9  24 ± 1 years	Isometric knee extension  SML = 50° LML = 100°  70% of MVIC  12 weeks, 4/week	SML: ↑Quadriceps muscle volume (10%, ES = 0.82) ↑EMG at all joint angles (3.1-7.5%, ES = 0.25-0.44)  LML: ↑Quadriceps muscle volume (11%, ES = 1.06) ↑Tendon stiffness (50.86%, ES = 1.22) ↓Tendon elongation (-14.01%, ES = 0.62) ↑EMG at all joint angles (7-8.84%, ES = 0.45-0.72)	SML: ↑MVIC at 40°, 50°, 60°, 70° and 80°  LML: ↑MVIC at 40°, 50°, 60°, 70°, 80°, 90°, 100° and 110°
Lindh (1979) <sup>40</sup> (13/20)	Healthy  F = 10  26.5 years	Isometric knee extension  SML = 15° LML = 60°  100% of MVIC  5 weeks, 3/week		SML: ↑MVIC in SML at 15° (32%) ↑MVIC at 60° (14%) ↑Con torque at 30°·s <sup>-1</sup>  LML: ↑MVIC at 15° (11%) ↑MVIC at 60° (31%) ↑Con torque at 30°·s <sup>-1</sup>

Noorkoiv, Nosaka, & Blazeovich (2014) <sup>32</sup> (17/20)	Healthy, untrained  M = 16  23.7 ± 4.0 years	Isometric knee extension  SML = 38.1 ± 3.7° LML = 87.5 ± 6.0°  100% of MVIC  6 weeks, 3/week	SML: ↑Mid VL fascicle length (5.6%, ES = 0.63)  LML: ↑Voluntary activation at 50° (ES = 0.53) and 60° (ES = 1.02) ↑Total quadriceps muscle volume (5.2%, ES = 0.19) ↑Distal VL fascicle length (5.8%, ES = 0.33)	SML: ↑MVIC at 40° and 50° (8.0-14.2%, ES = 0.34-0.54)
Noorkoiv, Nosaka, & Blazeovich (2015) <sup>33</sup> (17/20)	Healthy, untrained  M = 16  23.7 ± 4.0 years	Isometric knee extension  SML = 38.1 ± 3.7° LML = 87.5 ± 6.0°  100% of MVIC  6 weeks, 3/week		LML: ↑Concentric torque at 30, *60, *90, and 120°·s <sup>-1</sup> (10.1-13%, ES = 0.55-0.70)
Rasch & Pierson (1964) <sup>36</sup> (13/20)	Healthy, untrained university students  M = 29	Isometric elbow flexion  Single-angle = 3 sets at 90°  Multi-angle = 1 set at 60°, 90° and 120°  100% of MVIC  5 weeks, 5/week		
Sterling, (1969) <sup>35</sup> (18/20)	University physical education students  M = 120	Isometric “hip press”  SML = 25° MML = 55° LML = 85°  100% MVIC  7 weeks, 3/week		SML: ↑MVIC at 25° and 55° (21-37.2%)  MML: ↑MVIC at 25° and 55° (15.4-51.4%)  LML: ↑MVIC at 85° (3.1%)

Thepaut- Mathieu, Van Hoecke, & Maton (1988) <sup>37</sup>  11/20	Untrained  M = 24  31.8 years	Isometric elbow flexion  SML = 60° MML = 100° LML = 155°  80% MVIC  5 weeks, 3/week	SML, MML & LML: ↑EMG at all angles	SML: ↑MVIC at 60° and 80° (10-25%)  MML: ↑MVIC at 60-155° (22-30%)  LML: ↑MVIC at 80-155° (24-54%)
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SML = short muscle length. MML = medium muscle length. LML = long muscle length. MVIC = Maximal voluntary isometric contraction. Con = concentric. VL = vastus lateralis, VM = vastus medialis, RF = rectus femoris. 1RM = 1 repetition maximum. CMJ = Countermovement jump. ES = effect size (Cohen's *d*). \* denotes  $p > 0.05$ .

Table 2. Contraction intensity

Study, quality	Subjects	Intervention	Morphological and neural adaptations ( $p < 0.05$ , $ES \geq 0.50$ )	Performance effect ( $p < 0.05$ , $ES \geq 0.50$ )
Adamantios Arampatzis, Karamanidis, & Albracht (2007) <sup>41</sup> 14/20	Healthy, untrained university students  M = 7 F = 14  28 years	Isometric plantar flexion  LI = 55% MVIC (24 contractions) HI = 90% MVIC (16 contractions)  14 weeks, 4/week	LI: ↑Tendon elongation (16.2%, $ES = 0.56$ ) ↑Tendon strain (17.4%, $ES = 0.57$ ) ↑Calculated maximum tendon force (28.4%, $ES = 1.76$ )  HI: ↑Tendon stiffness (36%, $ES = 1.57$ ) ↑Tendon CSA at 60% and 70% of tendon length  ↑Calculated maximum tendon force (43.6%, $ES = 2.04$ )	
Adamantois Arampatzis, Peper, Bierbaum, & Albracht (2010) <sup>42</sup> 14/20	Healthy, untrained university students  M = 11  23.9 years	Isometric plantar flexion  LI = 55% MVIC (20 contractions) HI = 90% MVIC (12 contractions)  14 weeks, 4/week	LI: ↑Tendon elongation (14%, $ES = 0.84$ ) ↑Tendon strain (13.7%, $ES = 0.67$ ) ↑Calculated maximum tendon force (11.7%, $ES = 0.89$ )  HI: ↑Tendon stiffness (17.1%, $ES = 0.82$ ) ↑Calculated maximum tendon force (11.9%, $ES = 0.81$ )	
Kanehisa et al. (2002) <sup>44</sup> 16/20	Healthy, untrained  M = 12  27.5 years	Isometric elbow extension  LI = 60% MVIC (4 x 30s) HI = 100% MVIC (12 x 6s)	LI: ↑Muscle volume (5.3%, $ES = 0.26$ )  HI: ↑Muscle volume (12.4%, $ES = 0.28$ )	LI: ↑MVIC (61%, $ES = 1.91$ )  HI: ↑MVIC (60.3%, $ES = 2.71$ )

		10 weeks, 3/week		
Khouw & Herbert (1998) <sup>45</sup> 11/20	51 untrained university students  M = 18 F = 33	Isometric elbow flexion  Each subject assigned to an individual intensity between 0% and 100% in 2% increments  6 weeks, 3/week		Greater ↑MVIC (slope = 0.19, 5.3%, p = 0.006) when training closer to 100%
Szeto, Strauss, De Domenico, & Sun Lai (1989) <sup>46</sup> 11/20	University students  M = 6 F = 12	Isometric knee extension  LI = 25% MVIC MI = 50% MVIC HI = 100% MVIC  3 weeks, 5/week		LI: *↑MVIC (22.3%, ES = 0.61)  MI: ↑MVIC (31.3%, ES = 1.14)  HI: ↑MVIC (45.7%, ES = 1.44)
Young, McDonagh, & Davies (1985) <sup>65</sup> 12/20	Healthy  M = 4  20.5 years	Isometric plantar flexion  LI = 30% MVIC (7-15 x 60s) HI = 100% MVIC (3s contractions)  HI, 5 weeks; and LI, 8 weeks, 7/week		LI: ↑MVIC (3.3%/week) ↑MVIC (30.2%, ES = 2.22) ↑Fatigue index (19.4%, ES = 1.72)  HI: ↑MVIC (5.5%/week) ↑MVIC (21.2%, ES = 1.67)

LI = low intensity. MI = medium intensity. HI = high intensity. MVIC = maximal voluntary isometric contraction. ES = effect size (Cohen's *d*). \* denotes  $p > 0.05$ .



Table 3. Contraction intent

Study, year (quality)	Subjects	Intervention	Morphological and neural adaptations ( $p < 0.05$ , $ES \geq 0.50$ )	Performance effect ( $p < 0.05$ , $ES \geq 0.50$ )
Balshaw, Massey, Maden-Wilkinson, Tillin, & Folland (2016) <sup>43</sup> (15/20)	Healthy, untrained M = 43	Isometric knee extension  MST = 1s build to 75% of MVIC, hold for 3s (40 contractions)  EST = rapidly built to $\geq 80\%$ of MVIC and hold for 1s (40 contractions)  12 weeks, 3/week	MST: ↑Muscle volume (8.1%, $ES = 0.50$ ) ↑EMG at MVIC (27.8%, $ES = 0.67$ ) ↑EMG 0-150ms (14.3%, $ES = 0.36$ )  EST: ↑EMG 0-100 and 0-150ms (12.5-31.3%, $ES = 0.26-0.67$ )	MST: ↑MVIC (23.4%, $ES = 1.19$ ) ↑Force at 150ms (12.1%, $ES = 0.74$ )  EST: ↑MVIC (17.2%, $ES = 1.24$ ) ↑Force at 50, 100, 150ms (14.4-32.6%, $ES = 0.65-1.06$ )
Maffioletti & Martin (2001) <sup>48</sup> (17/20)	Healthy untrained M = 21	Isometric knee extension  RC = 4 seconds to reach MVIC BC = 1 second to reach MVIC  7 weeks, 3/week	RC: ↓VL EMG  BC: ↑Peak twitch (29.8%) ↓Contraction time ↓Maximal twitch relaxation	RC: ↑MVIC at 55°, 65° (15.7%) and 75° ↑Eccentric torque at 60°·s <sup>-1</sup> (15.6%) ↑Concentric torque at 60°·s <sup>-1</sup> and 240°·s <sup>-1</sup>  BC: ↑MVIC at 55°, 65° (27.4%) and 75° ↑Eccentric torque at 60°·s <sup>-1</sup> (18.3%) ↑Concentric torque at 60°·s <sup>-1</sup> and 240°·s <sup>-1</sup>
Massey, Balshaw, Maden-Wilkinson, Tillin, & Folland (2018) <sup>67</sup> (18/20)	Healthy untrained M = 42  MST = 25 ± 2 years  EST = 25 ± 2 years  CON = 25 ± 3 years	Isometric knee extension  MST = 1s build to 75% of MVIC, hold for 3s (~ 10 contractions)  EST = rapidly built to ~80% of MVIC (~ 10 contractions)  12 weeks, 3/week	MST: ↑Muscle volume (8.1%, $ES = 0.47$ ) ↑VL aponeurosis area (5.9%, $ES = 0.34$ ) ↑Tendon stiffness (14.3%, $ES = 0.79$ ) ↑Young's modulus (14.4%, $ES = 0.60$ ) ↑Tendon-aponeurosis stiffness (22.7%, $ES = 0.54$ )  EST: ↑VL aponeurosis area (4.4%, $ES = 0.38$ ) ↓Tendon CSA (2.8%, $ES = 0.31$ ) ↓Tendon elongation (11%, $ES = 0.75$ )	MST: ↑MVIC (23.6%, $ES = 1.17$ )  EST: ↑MVIC (16.7%, $ES = 1.23$ )

			<p>↑Tendon stiffness (19.9%, ES = 0.95)</p> <p>↓Tendon strain (11.8%, ES = 0.56)</p> <p>↑Young's modulus (21.1%, ES = 1.13)</p> <p>↑Tendon-aponeurosis elongation (16%, ES = 1.0)</p>	
<p>Tillin &amp; Folland (2014)<sup>47</sup></p> <p>(12/20)</p>	<p>Healthy, recreationally active male university students</p> <p>N = 19</p> <p>MST = 20.9 ± 1.1 years</p> <p>EST = 20.2 ± 2.4 years</p>	<p>Isometric knee extension</p> <p>MST = 1s build to 75% of MVIC, hold for 3s (10 contractions)</p> <p>EST = rapidly built to ≥ 90% of MVIC and hold for 1s (10 contractions)</p> <p>4 weeks, 4/week</p>	<p>MST:</p> <p>↑M-wave at MVIC (28.1%, ES = 1.28)</p> <p>↓%EMG at 50 and 150ms (11.7-22.1%, ES = 0.59-0.79)</p> <p>EST:</p> <p>↑M-wave at 50 and 100ms (25-42%, ES = 0.95-1.05)</p>	<p>MST:</p> <p>↑MVIC (20.5%, ES = 1.46)</p> <p>↑MVIC at 50, 100 and 150ms (3.09-7.39%, ES = 0.084-0.52)</p> <p>EST:</p> <p>↑MVIC (10.6%, ES = 0.56)</p> <p>↑MVIC at 50, 100 and 150ms (13.1-53.7%, ES = 0.96-1.2)</p>
<p>Williams (2011)<sup>66</sup></p> <p>(15/20)</p>	<p>Healthy, untrained university students</p> <p>M = 11 F = 12</p> <p>Ramp = 9 Ballistic = 8 22.8 years</p>	<p>Isometric knee extension</p> <p>RC = 4 seconds to reach MVIC BC = 1 second to reach MVIC</p> <p>6 weeks, 3/week</p>	<p>RC:</p> <p>↑Ramp VA (7.7%, ES = 1.99)</p> <p>↑Ballistic VA (8.3%, ES = 1.75)</p> <p>*↑150ms VA (9.82%, ES = 0.74)</p> <p>BC:</p> <p>↑Ramp VA (4.1%, ES = 1.07)</p> <p>↑Ballistic VA (7.9%, ES = 1.50)</p> <p>↑150ms VA (31.6%, ES = 1.84)</p>	<p>RC:</p> <p>↑Ramp MVIC (20%, ES = 1.95)</p> <p>↑Ballistic MVIC (17.8%, ES = 1.56)</p> <p>*↑150ms force (14.3%, ES = 1.10)</p> <p>BC:</p> <p>↑Ramp MVIC (15.7%, ES = 0.75)</p> <p>↑Ballistic MVIC (18.9%, ES = 0.88)</p> <p>↑150ms force (48.8%, ES = 3.66)</p>

MST = maximal strength training. EST = explosive strength training. RC = ramp contraction. BC = ballistic contraction. MVIC = maximal voluntary isometric contraction. VA = voluntary activation. ES = effect size (Cohen's *d*). \* denotes  $p > 0.05$ .

Table 4. Other independent variables

Study, quality	Subjects	Intervention	Morphological and neural adaptations ( $p < 0.05$ , $ES \geq 0.50$ )	Performance effect ( $p < 0.05$ and/or $ES \geq 0.50$ )
Kubo, Kanehisa, & Fukunaga (2001) <sup>13</sup>  14/20	Healthy, untrained  M = 8  22.6 years	Isometric knee extension  SC = 3 x 50 rapid contractions  LC = 4 x 20s  70% MVIC  12 weeks, 4/week	SC:  ↑Muscle volume (7.4%, $ES = 0.36$ )  *↑Tendon stiffness (17.5%, $ES = 0.57$ )  ↑Elastic energy (25.6%, $ES = 1.85$ )  LC:  ↑Muscle volume (7.6%, $ES = 0.38$ )  ↑Tendon stiffness (57.3%, $ES = 1.38$ )  ↑Elastic energy (12%, $ES = 0.58$ )	SC:  ↑MVIC (49%, $ES = 2.47$ )  LC:  ↑MVIC (41.6%, $ES = 2.21$ )
Meyers (1967) <sup>39</sup>  13/20	Healthy university students  M = 29	Isometric elbow flexion  LV = 3 x 6s  HV = 20 x 6s  100% MVIC  6 weeks, 3/week	LV:  ↑Muscle girth at 170° in trained arm  HV:  ↑Muscle girth at 170° in trained and untrained arm  ↑Muscle girth at 90° in trained arm	LV:  ↑MVIC at 170° (15.4%, $ES = 0.93$ )  *↑Muscle endurance (49.7%, $ES = 0.71$ )  HV:  ↑MVIC at 170° (15.5 %, $ES = 0.46$ )  *↑MVIC at 90° (9%, $ES = 0.50$ )  ↑Muscle endurance (42.7%, $ES = 0.67$ )

Schott, McCully, & Rutherford (1995) <sup>34</sup>	Healthy, untrained	Isometric knee extension	LC:  ↑Muscle ACSA at lower (11.1%) and upper (10.1%) femur	SC:  ↑MVIC (31.5%)  ↑Concentric torque at 120°·s <sup>-1</sup> and 180°·s <sup>-1</sup> (11.3-11.6%)  LC:  ↑MVIC at 90° (54.7%)
10/20	M = 1  F = 6  22.7 years	SC = 4 x 10 x 3s  LC = 4 x 30s  70% of MVIC  14 weeks, 3/week		
Ullrich, Holzinger, Soleimani, Pelzer, Stening, & Pfeiffer (2015) <sup>69</sup>	Healthy, active university students	Isometric knee extension	TP:  ↑Thigh circumference (6.2%, ES = 0.45)  ↑VL thickness at 25%, 50%, and 75% muscle length (15.5-18.5%, ES = 0.98-1.23)  ↑VL fascicle length (13.7%, ES = 1.17)  ↑MVIC EMG (45%)  DUP:  ↑Thigh circumference (5.0%, ES = 0.37)  ↑VL thickness at 25%, 50%, and 75% muscle length (12.4-19.7%, ES = 0.72-1.01)  ↑VL fascicle length (14.2%, ES = 0.90)  ↑MVIC EMG (46%)	TP:  ↑MVIC (24%)  ↑Concentric torque at 60°·s <sup>-1</sup> (19%)  DUP:  ↑MVIC (23%)  ↑Concentric torque at 60°·s <sup>-1</sup> (15%)
16/20	F = 10  24.4 ± 3.2 years	TP limb = 3 weeks 60%, 4 weeks 80%, 3 weeks 60%, 2 weeks 80% of MVIC  DUP limb = Alternating sessions at 60% and 80% of MVIC in one limb  16 weeks, 2/week		

Waugh, Alktebi, De Sa, & Scott (2018) <sup>68</sup>  14/20	Healthy, physically active  M = 8 F = 10  30.1 ± 7.9 years	Isometric plantarflexion  SR = 3s between reps LR = 10s between reps  90% MVIC  12 weeks, 3/week	SR: ↑Echo-type II (collagen re-organization)  SR & LR: ↑Stiffness ↑Tendon stress ↑Young's modulus ↓Strain % ↓Tendon elongation	SR & LR: ↑MVIC
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SC = short contraction. LC = long contraction. LV = low volume. HV = high volume. SR = short rest. LR = long rest. TP = traditional periodization. DUP = daily undulating periodization. MVIC = maximal voluntary isometric contraction. ES = effect size (Cohen's *d*). \* denotes  $p > 0.05$ .



