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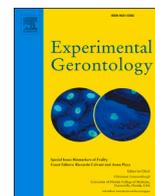
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Evidence of resistance training-induced neural adaptation in older adults

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ABSTRACT

The deleterious effects of aging on force production are observable from the age of 40 upwards, depending on the measure. Neural mechanisms contributing to maximum force production and rate of force development have been suggested as descending drive from supraspinal centers, spinal motoneuron excitability, and corticospinal inhibition of descending drive; all of which influence motor unit recruitment and/or firing rate. Resistance-trained Master athletes offer a good source of information regarding the inevitable effects of aging despite the countermeasure of systematic resistance-training. However, most evidence of neural adaptation is derived from longitudinal intervention studies in previously untrained (i.e. resistance-training naïve) older adults. There is good evidence for the effect of resistance-training on the end-point of neural activation, i.e. motor unit behavior, but little to no data on the generation of descending drive from e.g. transcranial magnetic stimulation or cortical imaging studies in older adults. This, along with tracking master athletes over several years, would provide valuable information and could be the focus of future research.

1. Introduction

Aging is a biological process of serial deleterious cellular changes that begin in early life (Kinzina et al., 2019). Nevertheless, the consequence of such accumulated serial changes is often not observable until mid- to later-life. Regarding the ability to produce maximal force, i.e. strength, age-related losses become apparent from approximately the age of 50 and the rate of loss is reported as ~1.5% per year (Frontera et al., 1991; Skelton et al., 1994). This age-related loss of maximal force production is meaningful in daily living as it can predict e.g. walking speed and stair-climbing ability (Rantanen et al., 1994). Some authors have suggested that the ability to produce force rapidly is more critical than maximum force capacity for daily living (Basseley et al., 1992; Evans, 2000), and age-related losses of power are already observable after the age of 40 (Kostka, 2005; Van Roie et al., 2018). Averaged over ages 40–80 y, peak power decreased at a rate of ~1.4% in men and ~1.3% in women per year (Van Roie et al., 2018). However, losses of 3.5% per year have been reported above the age of 65 (Skelton et al., 1994), suggesting an accelerating trajectory with increasing age that exceeds losses in maximum force production. As has been shown (Rantanen et al., 1994; Van Roie et al., 2011), the ability to produce high force levels and increase force rapidly is an important factor in combatting age-related loss in function staving off the development of mobility-restricted disability.

Neural mechanisms play an important role in force production, and neural adaptations could occur due to improved agonist and synergist activation, as well as reduced coactivation of antagonist muscles. Improved agonist activation could potentially occur through greater motor unit recruitment or motor unit firing rate (i.e. the rate at which the motor unit is activated) due to increased descending drive from supraspinal centers, spinal motoneuron excitability, and/or reduced spinal inhibition of descending drive (Aagaard and Thorstensson, 2003). For example, rapid force production over the initial 25–75 ms of contraction appears to be governed by the ability to recruit motor units at a high firing rate (Duchateau and Baudry, 2014; Del Vecchio et al., 2019). Improvements in motor unit recruitment strategy are trainable, as shown in the classic study by Van Cutsem et al. (1998), and this is accompanied by improved rapid force production. Importantly, motor unit firing rate can distinguish between young and older adults, with older adults showing lower firing rates, concomitant with differences in rate of force development (Klass et al., 2008). Therefore, there is a need for training programs targeting neural adaptations in order to maintain (rapid) force production and, by extension, functional capacity during aging. While various forms of exercise are recommended to improve different aspects of fitness, resistance-training is most effective to improve maximal and rapid force production. Indeed, older adults that were long-term resistance-trained showed similar levels of peak power at 80 years old to <60 year-old sedentary adults (Pearson et al., 2002).

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Studies with small sample sizes (e.g. Kraemer et al., 1999, Welle et al., 1996, $n < 10$ per group) have suggested that young have an advantage over older adults in terms of the resistance training-induced magnitude of increased strength and muscle mass. However, larger scale studies (e.g. Ahtiainen et al., 2016, $n > 25$ per group) and meta-analyses (Guizilini et al., 2018, $n > 100$ per group) do not seem to support this view, with a potential exception of >80 year-olds for hypertrophy (Grgic et al., 2020, $n > 35$ per group). For example, Ahtiainen et al. (2016) observed increases in leg press one-repetition maximum of $\sim 19\%$ (<45 y), $\sim 19\%$ (45–60 y) and $\sim 20\%$ (>65 y) in men and $\sim 27\%$ (<45 y), $\sim 20\%$ (45–60 y) and $\sim 27\%$ (>65 y) in women after training for 20–24 weeks with no significant interaction for sex*age group. In the meta-analysis of Guizilini et al. (2018), resistance training over 4–16 weeks in older age was potent in improving both rapid and maximum force production, and meta-regression showed that age did not influence the results; although a possible effect of sex was not assessed in this study. Consequently, it may be assumed that previously untrained individuals (unfamiliar with resistance-training) have the same potential for improvements over an initial 6-month period in force output and neuromuscular adaptations regardless of age or sex. It may be that adaptability is regulated by several factors related to the individual's genetic propensity, how the training is performed, and perhaps also nutritional habits, to name a few, rather than age per se.

Quite strikingly, there is no systematic review or meta-analysis detailing the efficacy of resistance-training to elicit neural adaptations in older adults to my knowledge; which may be symptomatic of the varied methodology used to quantify neural adaptations, lack of sufficient number of studies in older adults, or simply the indirect nature of the currently available (non-invasive) methodology in humans. This mini-review will summarize some of the studies performed in this area, and also provide some possibilities for future research to enhance our understanding of resistance training-induced neural adaptation in older adults.

Before delving into the scientific evidence of neural adaptation from resistance-training, there are some issues that should be addressed. For clarity, the term “older adult” used in the present paper refers to adults above 60 years old, given that many of the studies included in this mini-review recruited subjects of such age; despite the World Health Organization assigning the transition into older adulthood at 65 years in its “Guidelines on Physical Activity and Sedentary Behaviour” (WHO, 2020). Secondly, it should be stated that the aim of this mini-review is not to directly compare neuromuscular properties of young and older adults, nor does it detail neurophysiological consequences of the aging process per se. For such information, interested readers are directed to other extensive reviews e.g. by Hunter et al. (2016). Rather this narrative review focusses on the effect of resistance-training, in the short- and long-term, on neural mechanisms concomitant with maintained or improved high/rapid force production.

2. Cross-sectional studies

It is not feasible to study the effects of decades of resistance-training experience in a randomized, controlled trial. Nevertheless, one way to gain knowledge regarding the effects of long-term resistance-training on neural mechanisms of force production is to cross-sectionally examine individuals who have maintained high levels of training, and subsequently force production, throughout older age. Master athletes provide a rich source of physiological information as this population largely removes the typical confounding factor of decreased physical activity levels from aging itself (Lazarus and Harridge, 2007). There remains the issue of genetic predisposition possibly affecting the findings, i.e. those with neuromuscular characteristics suited for power events gravitating toward competing in such sports, as well as potential cohort effects. There is currently no study using twins discordant for resistance-training that could also address these confounding factors; perhaps due to the rarity of locating such discordant twin-pairs.

2.1. Evidence of improved agonist activation from resistance training

As mentioned above, elite 40–87 year-old weightlifters demonstrated $\sim 32\%$ greater peak power than age matched controls, but they also demonstrated a $\sim 1.2\%$ loss of power after the age of 45 (Pearson et al., 2002). One study that provided indirect evidence of preserved neural mechanisms in Master athletes is by Ojanen et al. (2007). Tested with a maximal bilateral isometric leg press action, the authors showed that the men athletes produced $\sim 23\%$ and $\sim 28\%$ lower maximum force compared to 40 year-old athletes at approximately 60 and 75 years old, respectively. However, when normalized to quadriceps muscle thickness, the decreases in relative maximum force were only $\sim 5\%$ and $\sim 6\%$ in the abovementioned age-groups; suggesting that the majority of the observed age-related decreases in maximum force was due to reduced muscle mass. Furthermore, age-matched control men showed reduced relative maximum force of $\sim 18\%$ (40 y), $\sim 29\%$ (60 y), and $\sim 37\%$ (75 y) compared to the 40 year-old athletes (Ojanen et al., 2007), highlighting their inability to fully activate the quadriceps muscles compared to the athletes.

Despite the methodological limitations of bipolar surface electromyography (sEMG) to interpret neural activation of the muscle (Farina et al., 2014), bipolar sEMG amplitude has been considered a gross signal representing motor unit recruitment and firing rate of the detected motor units; potentially due to the close relationship between force and sEMG amplitude (Alkner et al., 2000; Felici and Del Vecchio, 2020). It is unfortunate that Ojanen et al. (2007) did not directly compare normalized sEMG amplitude of athletes to age-matched controls. However, sEMG amplitude over the initial 100 ms of leg press action, normalized to sEMG amplitude from the maximum (plateau) force phase, showed significant reductions in all athlete age-groups except in the 40 year olds (Ojanen et al., 2007). This reduced sEMG amplitude accompanied large reductions in rapid force production from the 40 to the 75 year-olds (approx. 50% loss). Nevertheless, the 75 year-old athletes still had greater rapid force production capacity than 40 year-old controls.

Aagaard et al. (2007) investigated potential differences between 50-year resistance-trained, endurance-trained and healthy but untrained men aged ~ 70 years old. Again, indirect evidence of preserved neural mechanisms in resistance-trained individuals was provided. Maximal unilateral knee extensions were performed, with both resistance- and endurance-trained groups showing greater maximum isometric force than the untrained group. However, the resistance-trained group outperformed the endurance-trained and untrained groups in rapid force production over 30 ms and 50 ms, which is purportedly predominantly influenced by motor unit firing rate (Del Vecchio et al., 2019; Maffiuletti et al., 2016). While peripheral factors, such as fiber type composition and tendon stiffness, could affect rapid force production, Aagaard et al. (2007) found no systematic differences in type I:II ratio that may muscular factors led to the observed between-group differences (Strength group = $\sim 61:39$, Endurance group = $\sim 67:33$, control group = $\sim 47:53$). The highlighted studies show that the ability to rapidly activate muscle is impaired during aging despite a high training volume, and that chronic resistance-training appears to partially maintain neural mechanisms influencing force production. Further, aging alongside sedentary behavior demonstrates the greatest depletion in the ability to activate motor units.

More direct evidence of greater motor unit firing rate in Master athletes was provided by Leong et al. (1999). Intramuscular (needle) electrodes were inserted into m.vastus lateralis of five competitive weight-lifting men and five age-matched controls (~ 70 years-old). Recordings were taken during maximal isometric knee extensions using four-wire needle electrodes obtaining data from several sites of the muscle. A total of 13–20 maximal contractions were performed in the test session with 5 min rest between trials. Firing rates were determined from the five shortest consecutive firings from 50 individual motor unit firings. The authors noted that the maximal motor unit firing rate was

greater ($P < 0.05$) in the weight-lifters (~24 pps) than controls (~19 pps), which accompanied the expected difference in maximum force production (367 vs 300 N, $P < 0.05$). To provide perspective, in healthy but non-resistance trained subjects, Kamen and Knight (2004) observed maximal motor unit firing rates of ~25 pps in young (~21 y) and ~18 pps in older (~77 y) adults using the same methods. These combined findings show that the long-term older weight-lifters have comparable motor unit firing rates to untrained young adults, but that untrained older adults have lower motor unit firing rates.

Finally, one study used peripheral electrical stimulation techniques to assess descending drive and voluntary activation percentage to the calf muscles between ~70 year-old Master men athletes and both recreationally active and sedentary age-matched control men (Unhjem et al., 2016). The V-wave is a variant of the H-reflex that can assess descending drive during maximal voluntary contraction. The amplitude of the H-reflex from supramaximal stimulation intensity allowed to pass to the muscle (i.e. the so-called V-wave) reflects the collisions of antidromic and orthodromic action potentials near the spinal cord (Aagaard et al., 2002). Hence, the greater the descending drive, the greater the collision and cancellation of antidromic action potentials from the electrical stimulation and the larger the V-wave amplitude. During maximum isometric action, Master athletes showed higher normalized V-wave amplitude versus both other groups, and also higher voluntary activation assessed by the interpolated twitch technique. The results suggest that long-term resistance-training can maintain the ability to maximally activate the muscles via greater descending drive, affecting motor unit recruitment and/or firing rate, whereas recreational activities do not.

2.2. Evidence of maintained motor unit integrity from resistance training

In addition to motor unit recruitment and firing rate, another potential consequence of aging is the selective denervation and loss of motoneurons activating type II muscle fibers, as observed in rats (Kadhiresan et al., 1996). Although conflicting results of muscle fiber distribution have been shown from muscle biopsy samples of m.vastus lateralis (e.g. Larsson et al., 1978 vs. Lexell et al., 1988), close fiber-type grouping with advancing age suggests that the proposed denervation/reinnervation cycles are a plausible neuromuscular adaptation during normal aging (Lexell et al., 1986). Maintaining diverse fiber type distribution is naturally advantageous for force production, and especially maintaining the integrity of type II motoneurons/motor units (whose firing rate is higher than type I motor units) is of predominant importance for rapid force development.

Using a combination of supramaximal peripheral electrical stimulation and bipolar sEMG recordings from a series of voluntary actions, some researchers have attempted to estimate the number of motor units within a muscle. Using a cohort of both men and women, Drey et al. (2016) showed that >65 year-old preferentially power-trained track & field athletes had a greater motor unit number index compared to untrained >65 year-olds ($P = 0.032$) in a hand muscle. The difference between endurance-trained and untrained controls was at the level of a trend ($P = 0.052$) and no differences between power-trained and endurance-trained athletes were observed ($P = 0.741$) (Drey et al., 2016). However, such evidence in a non-training-specific muscle and with limited distinction between resistance- and endurance-trained individuals does not provide strong support for the resistance-training modality.

Using invasive intramuscular EMG techniques, it appears that Master athletes are not spared motoneuron denervation that untrained controls demonstrate (Piasecki et al., 2016; Power et al., 2012). Here, the spike-triggered averaging method was used from intramuscular EMG to time-synchronize sEMG signals to generate surface motor unit potentials recorded during isometric contractions of 10% (Power et al., 2012) and 25% (Piasecki et al., 2016) of maximum force. To estimate motor unit number, the electrically-evoked negative peak amplitude of the

compound motor action potential is divided by the negative peak amplitude of the mean surface motor unit potential (Power et al., 2012). Both studies showed that Master athletes had similar motor unit number estimates compared to recreationally active older adults (~70 y) but lower ($P < 0.05$) motor unit number estimates than the young (~26 y). However, it may be that higher levels of training stimulate greater rates of reinnervation in lower limb muscles (Piasecki et al., 2016; Piasecki et al., 2019; Piasecki et al., 2021). Thereby, while motor unit number would decrease and a tendency for a slower phenotype, the neural adaptation of reinnervation would help to preserve the number of muscle fibers in the muscle and overall force production capacity. Despite this interpretation, the reader should be aware of the methodological limitations of these studies, such as evaluating motor unit behavior during low force actions (e.g. $\leq 25\%$ of maximum) and/or assessing non-trained muscles of the upper limb for example, and place the conclusions within this context.

As the above studies were cross-sectional observations, it is not known whether the existing differences between resistance-trained and untrained individuals exists because of the exercise modality or genetic propensity, e.g. greater number of (type II) motor units from birth, which may have led to them selecting to complete in power-oriented athletic events. Furthermore, cross-sectional observations are also limited by potential cohort effects; e.g. different generations have lived through differing life-circumstances, medical advancements, and progressions in standard of living, which confound direct comparison of 20, 40, 60 and 80 year-olds. Therefore, cause and effect cannot be established. From a study design perspective, an ideal scenario would be to track neuromuscular properties in Master athletes from middle- to older-age in comparison with the adaptations demonstrated by untrained/sedentary controls. Hence, perhaps the best evidence of resistance training-induced neural adaptations currently available comes from short-term intervention studies in previously untrained older adults.

3. Longitudinal (intervention) studies

The classic study by Moritani and DeVries (1979) described that previously untrained individuals improve force production primarily through neural mechanisms in the early weeks of training (i.e. <6 weeks) followed by predominantly muscular adaptations thereafter. Based on this framework, early resistance-training studies suggested that neural adaptations had occurred based on disproportionate increases in force production capacity and muscle hypertrophy (Dons et al., 1979; Jones and Rutherford, 1987). However, to gain insight into the source(s) of neural adaptation, various neurophysiological techniques have been subsequently used.

3.1. Evidence from surface EMG

The most abundant evaluation method used to provide evidence of training-induced neural adaptation is bipolar sEMG amplitude. As mentioned above, relying solely on bipolar sEMG to determine neural adaptation does not allow firm conclusions since there are other factors contributing to the signal (Farina et al., 2014). Furthermore, simulation studies have shown that muscular adaptations can also influence changes in the amplitude of the sEMG signal (Arabadzhiev et al., 2014). Therefore, the results presented here should be framed within that context of uncertainty.

The vast majority of training studies in older adults have shown increases in bipolar sEMG amplitude in both the initial time period (e.g. <100 ms) and during the maximum force plateau of isometric actions, as well as during maximum concentric actions (Correa et al., 2012, Häkkinen et al., 1998, Häkkinen et al., 2001, Moritani & deVries, 1980, Suetta et al., 2004, Walker et al., 2014, Walker and Häkkinen, 2014). Such increases may indicate increased motor unit recruitment, increased firing rate of recruited motor units, or both. Alternatively, increased prevalence of motor unit synchronization would also serve to increase

sEMG amplitude (Yao et al., 2000). Supporting the importance of the underlying adaptations observable in the sEMG signal, significant relationships between the increase in force and the increase in sEMG amplitude have been observed (e.g. Holviala et al., 2012; Walker et al., 2014). Interestingly, some studies have reported continued increases even up to 6 months in older individuals after beginning a resistance training program (Häkkinen et al., 1998; Häkkinen et al., 2001; Walker et al., 2014) despite neural adaptations thought to occur predominantly during the initial weeks of training. This finding may be in response to progression in-built within the long-term training program or also symptomatic of limitations within the bipolar sEMG method.

Although it is also possible that force production could increase due to reduced antagonist coactivation, the dearth of evidence provided suggests that this is not a major factor in the strength gains of older adults due to resistance-training. While reduced antagonist coactivation would be advantageous for force production, antagonist coactivation serves to stabilize the joint and possibly protect against injury to connective tissue (Baratta et al., 1988). Thus, there is a trade-off between maximum force production and maintaining joint/tissue integrity. Secondly, greater joint stability is an important characteristic to preserve in older individuals who may be at greater risk of e.g. falls due to compromised force production capacity and reflex responses. To my knowledge, only two studies have shown decreased antagonist coactivation in older adults (Häkkinen et al., 1998; Häkkinen et al., 2000). It is not clear why there is a general lack of data on coactivation ratio. However, it may be speculated that the studies of Häkkinen et al. (1998, 2000) observed decreases in subject groups with excessively large pre-training coactivation (>25%); since the older groups reduced coactivation toward the level of tested younger groups (~20%).

A fairly recent sEMG analysis technique to assess neural adaptation to resistance-training, although the technique itself is not novel, is intramuscular coherence (i.e. EMG-EMG). Here, the correlation between two EMG signals in the frequency domain is calculated to infer the strength of the connections of different parts of the nervous system. For more detailed information, the interested reader is directed to the work of Stuart N Baker's group, among others. Taking a simplistic viewpoint, it is thought that lower frequencies (<15 Hz) reflect spinal-level processes while ~15–40 Hz reflect cortical and corticospinal processes; coherence at lower frequencies persist following complete spinal cord injury whereas ~15–40 Hz coherence is abolished (Aguilar et al., 2018) and ~15–40 Hz coherence can recover during rehab when the injury is incomplete (Norton and Gorassini, 2006). Highlighting the potential validity of this method, abnormal motor evoked potentials from transcranial magnetic stimulation (a measure of corticospinal excitability) and abolished coherence at 15–30 Hz was observed in motor neuron disease patients, whereas both motor evoked potential and EMG-EMG coherence was preserved in muscular atrophy patients relative to healthy controls (Fisher et al., 2012). There is also evidence that increased excitability of the corticospinal tract from short-term training can be detected though EMG-EMG coherence techniques. Incomplete spinal cord injury patients showed increased EMG-EMG coherence at 24–40 Hz during walking trials following a walking intervention, which was associated with increases in motor evoked potentials (Norton and Gorassini, 2006). However, despite older adults demonstrating lower coherence in both 8–14 and 16–30 Hz during 20% and 70% maximum force knee extensions than young adults, there were no increases in either group over 14 weeks of resistance-training (Walker et al., 2019). This methodology may lack sensitivity to detect the subtle neural adaptations in healthy subjects before and after resistance-training, but further studies are needed to confirm whether the null finding is the norm. In particular, verification of EMG-EMG coherence reliability and e.g. standard error would be a valuable addition to the literature if this method is to be used in training studies in the future.

3.2. Evidence from intramuscular EMG

Building from the seminal work from Van Cutsem et al. (1998) in young adults, Professor Kamen's group has provided several studies showing increased firing rates at maximum force levels in older adults following a period of (isometric and dynamic) resistance-training in various muscles (Christie and Kamen, 2010; Kamen and Knight, 2004; Patten et al., 2001). Overall, the increases in maximal firing rate were observed during the baseline testing period or very early in the training program (<2 weeks), and thereafter there were no further increases (Kamen and Knight, 2004) or even a return to baseline (Patten et al., 2001). It is difficult to discern the cause of the discrepancy between these findings and the more prolonged increases of sEMG; reported as long as 6 months (Häkkinen et al., 1998). Perhaps methodological issues such as replacement of the electrodes and the narrow spatial recording of motor units could influence data variability. Alternatively, it may be that firing rate has a greater influence on the rate of force development (Duchateau and Baudry, 2014; Del Vecchio et al., 2019) and progressive increases of force than the maximum force production (i.e. force plateau) per se. In a recent study using multi-channel sEMG to decompose the signal and evaluate motor unit behavior, Watanabe et al. (2018) observed increased firing rate over 6 weeks of training but only at submaximal forces (30–80% max. force) and predominantly in motor units recruited at low force levels (<20% max. force). Nevertheless, intramuscular and, likely more readily used in the future, multi-channel sEMG have shown evidence of increased motor unit firing rate over the initial few weeks of resistance-training in older adults.

3.3. Evidence from peripheral electrical stimulation

As an indicator of the ability to fully activate the muscle (i.e. 100% activation), the interpolated twitch technique is relatively simple to perform and non-invasive despite causing some discomfort when assessing some muscles e.g. the quadriceps. Thereafter, the maximum voluntary torque can be expressed relative to the additional torque produced by the supramaximal electrical stimulation (the central activation ratio), or the additional torque produced by the stimulation can be expressed relative to the twitch torque produced during rest immediately after the maximum voluntary isometric action (voluntary activation percentage). Possibly the first study to use this method in older individuals was Harridge et al. (1999). Here, 85–97 year-olds from a geriatric hospital were tested before and after 12 weeks of resistance-training performed three times per week. Pre-training voluntary activation values were 69–93%, indicating inability to fully activate the quadriceps muscles. On a group-level, there were no statistically significant changes over the training period. The twitch interpolation method has been shown to lack sensitivity in detecting changes (Herbert & Gandevia, 1999), which may help to explain some of the lack of statistical significance in some studies (Harridge et al., 1999; Unhjem et al., 2021). Nevertheless, the training-induced increases in voluntary activation percentage were related to the increases in maximum force production on an individual level ($r = 0.92$, $P < 0.005$). It is possible that the lack of group-level change was influenced by the high variability demonstrated by older adults from this method (Hunter et al., 2016).

Using the central activation ratio method, Knight and Kamen (2001) observed a statistically significant ~2% increase in a group of 67–81 year-olds over a 6-week period. Similarly, Walker and Häkkinen (2014) observed significant increases in voluntary activation percentage from ~91% to ~93% over 10 weeks in the quadriceps, and Scaglioni et al. (2002) observed increases from ~95% to ~98% over 16 weeks in the plantarflexors. Apart from greater age and level of frailty in the Harridge et al. (1999) study and the lower training volume employed by Unhjem et al. (2021), it is difficult to assign potential methodological reasons for the conflicting findings. Most studies have utilized medium-intensity (e.g. 70–85% maximum load) and high-volume (e.g. 3–4 sets of 8–12 repetitions) at a frequency of 2–3 times per week. Although, as

mentioned, the likely magnitude of change due to short-term training is only 2–3% on average and measured activation level is highly variable in older adults. Therefore, negative or null changes in one or two subjects in a group can greatly influence statistical power in such studies. As with sEMG amplitude, both motor unit recruitment and firing rate contribute to the voluntary activation level and so the precise neural adaptation cannot be determined.

Peripheral electrical stimulation has also been used to measure V-wave amplitude. Since increased V-wave amplitude has been shown to indicate improvements in descending drive from resistance-training (Aagaard et al., 2002), a group from Trondheim, Norway have performed a series of studies in m. soleus of >65 year-olds. These studies have consistently shown increases in normalized V-wave responses elicited during maximum isometric actions from between 3 and 8 weeks resistance-training (Toien et al., 2018; Unhjem et al., 2015; Unhjem et al., 2021). Therefore, data from electrical stimulation studies suggest resistance training-induced increases in motor unit recruitment/firing rate, possibly through greater descending drive, in older adults occur over the initial weeks of training.

3.4. Evidence from transcranial magnetic stimulation

For a more complete understanding of available methodology and findings from resistance-training studies using transcranial magnetic stimulation in general, the reader is directed to a recent review and meta-analysis by Siddique et al. (2020). For brevity, this method can e.g. provide information regarding corticospinal excitability through examining the sEMG-recorded amplitude of the motor evoked potential or level of corticospinal inhibition through examining the silent period or using double-pulse stimulation methods eliciting short- and long-interval cortical inhibition. In older adults, one study has been performed over a 2-week resistance-training period (Christie and Kamen, 2014). Whereas motor evoked potential amplitude during rest did not change, the duration of the silent period shortened during isometric dorsiflexion action with 50% of maximum force; indicating lower cortical inhibition after training. These findings closely match meta-analysis data of healthy young adults (Siddique et al., 2020) highlighting that it is important to test motor evoked potentials during voluntary contraction and, secondly, some level of inhibition is reduced through resistance-training in both young and older adults. It is not completely understood where the removal of inhibition occurs. The classical interpretation is that intracortical inhibition, influenced by GABA_A, is the prime candidate to affect silent period duration. However, Renshaw cells increase spinal inhibition in the immediate aftermath of cortical stimulation (Fuhr et al., 1991) and this can affect the silent period, whereas latter stages of the silent period seem more related to cortical inhibition (Yacyshyn et al., 2016). Hence, changes in silent period duration could be of cortical and/or spinal origin. Nevertheless, removal of such inhibition would serve to increase descending drive and fit with the data from peripheral nerve stimulation.

Currently, no work has compiled the different methodological approaches highlighted in this mini-review to determine which data reflect the same neural adaptations. Perhaps using such a combined approach would improve the accuracy of the data-based interpretations.

4. Conclusions and suggestions for the future

Resistance-training is a potent stimulus to increase maximal force production capacity and rate of force development in previously untrained older adults. Continued resistance-training also serves to better maintain force production capacity in Master athletes compared to age-matched controls. Accompanying these greater strength levels in athletes as well as after short-term resistance-training is evidence of greater motor unit recruitment and motor unit firing rate. Such observations have been made through various different methodologies, and the occurrence of such observed neural adaptation outweighs null findings

in the literature. These *end-point* adaptations in motor unit behavior may be due to enhanced descending drive, at least partly through reduced corticospinal inhibition. However, scientific investigation into corticospinal adaptation is scarce in older adults.

To improve our understanding of neural adaptation from resistance-training in older adults, tracking Master athletes over years alongside sedentary twins or age-matched controls would be novel. This would allow firmer conclusions to be made regarding the efficacy of resistance-training to maintain neuromuscular function through a more robust study design (albeit a more challenging one). Additionally, more data in women athletes would be welcome. Secondly, resistance-training studies using transcranial magnetic stimulation, as well as spinal level assessment (e.g. electrical stimulation) would improve the knowledge base on corticospinal factors influencing motor unit behavior and force production. Here, a combined methodological approach may be worthwhile. Finally, there is a lack of resistance-training studies using cortical imaging methods such as electroencephalography or magnetoencephalography. Expanding into this area of neurophysiology may provide exercise scientists with a better understanding of the generation and modification of descending drive at the cortical level.

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