A comparison of volume equated knee extensions to failure, or not to failure, upon rating of perceived exertion and strength adaptations

<table>
<thead>
<tr>
<th>Journal:</th>
<th>Applied Physiology, Nutrition, and Metabolism</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manuscript ID</td>
<td>apnm-2015-0421.R2</td>
</tr>
<tr>
<td>Manuscript Type:</td>
<td>Article</td>
</tr>
<tr>
<td>Date Submitted by the Author:</td>
<td>20-Oct-2015</td>
</tr>
</tbody>
</table>
| Complete List of Authors: | Fisher, James; Southampton Solent University, Centre for Health, Exercise and Sport Science  
|                     | Blossom, Dominic; Southampton Solent University, Centre for Health, Exercise and Sport Science  
|                     | Steele, James; Southampton Solent University, Centre for Health, Exercise and Sport Science  |
| Keyword:          | resistance training < exercise, isometric strength, untrained males |

https://mc06.manuscriptcentral.com/apnm-pubs
A comparison of volume equated knee extensions to failure, or not to failure, upon rating of perceived exertion and strength adaptations

Fisher, James Peter¹; Blossom, Dominic¹; Steele, James.¹

¹ Southampton Solent University, East Park Terrace, Southampton, UK

Corresponding Author:
James Fisher
Southampton Solent University
East Park Terrace
Southampton
UK
Tel: +44 2380 319000
Fax: +44 2380337438
Email: james.fisher@solent.ac.uk

Co-Author contact details:
Dominic Blossom (Dominic.Blossom@hotmail.co.uk)
James Steele (James.steele@solent.ac.uk)
Abstract

The present study aimed to compare the effects of repetition duration-, volume- and load-matched resistance training to momentary muscular failure (MMF) or not to muscular failure (NMF) on maximal voluntary isometric knee extensor strength. This design also allowed testing of the efficacy of ‘5x5’ training. Nine recreationally active males (21.4 ±1.2 years; 1.79 ± 0.07 m; 78.4 ±7.1 kg) performed unilateral resistance training at 80% of max torque 2 x / week for 6 weeks. Using their non-dominant leg participants performed 5 sets of 5 repetitions (NMF). Using their dominant leg participants performed 25 repetitions in as few sets as possible (MMF). All repetitions were performed at a pace of 2s concentric, 1s isometric pause, and 2s eccentric with a 2-minute rest interval between sets. Analyses identified significant pre- to post-intervention strength increases for both MMF and NMF, with effect sizes (ESs) of 2.01 and 1.65, respectively, with no significant differences between conditions ($p > 0.05$). Peak and mean RPE was significantly higher for MMF compared to NMF conditions ($p < 0.0001$), and a tendency for significantly higher RPE values reported for later sets for the NMF condition. Total training time per session was significantly longer for NMF compared to MMF ($p < 0.001$). The present study suggests that in untrained participants resistance training NMF produces equivalently the same strength increases as training to MMF when volume matched. However, RT to MMF appears a more time-efficient protocol and may produce greater strength gains as indicated by a larger ES.

Key words: resistance training, isometric strength, untrained males
Introduction

Resistance training (RT) is evidenced to show considerable benefits for athletic participants (e.g. strengthening joints, muscles, tendons and bones, and improving power, speed, and vertical jump; Stone, 1990). In addition, the accompanying strength increases are evidenced to provide numerous health related benefits (Westcott, 2012) and even reduce risk of all-cause mortality in the lay population (Newman et al. 2006; Ruiz et al. 2008; Volaklis et al. 2015). With this in mind a plethora of research has considered the variables associated with RT (e.g. volume, load, frequency, and repetition duration,), and has been summarised in numerous review articles to attempt to most efficiently prescribe this exercise modality (Ratamess et al. 2009; Fisher et al. 2011).

An important variable within RT is that of intensity of effort (Steele, 2014) and whether a person should exercise to momentary muscular failure (MMF). This has been defined as the “inability to perform any further concentric contractions without significant change to posture or repetition duration, against a given resistance” (Fisher et al. 2011). Previously it has been suggested that evidence supports training to MMF to enhance motor unit recruitment and growth-promoting hormones, but also advised that the method not be continued over long periods for risk of potential overtraining and overuse injuries (Willardson, 2007).

Henneman’s size principle states that, as smaller, lower threshold motor units (MU) fatigue, so larger, higher threshold MUs are recruited. MMF occurs when there is an inability to continue innervating MUs and/or a reduction in rate of discharge (rate coding; Enoka & Duchateau, 2008). By this rationale, exercising to MMF seems a practical method of ensuring recruitment of all available muscle fibres. However, whilst some research has
5 x 5 training vs. Training to failure

supported that training to MMF appears the most efficacious method of inducing strength adaptations (Rooney et al. 1994; Schott et al. 1995; Drinkwater et al. 2005; Giessing et al. 2014), other research has suggested equivalent gains when not training to failure (NMF; Izquierdo et al. 2006; Folland et al. 2002; Sampson & Groeller, 2015). In addition that many of these studies have methodological discrepancies complicates understanding of this variable.

Willardson et al. (2010) previously suggested that research studies considering this area have significant limitations. For example: Izquierdo, et al. (2006) instructed all repetitions for the measured exercises to be performed at “the highest possible speed” suggesting that, irrespective of total volume or achieving MMF, the explosive nature of the repetitions might have been sufficient to maximally recruit available MUs¹. Sampson and Groeller (2015), in attempting to assess and equate relative load between groups, required all participants to perform “a single set of elbow flexion to failure once each week” – a considerable limitation in a study professing to compare RT to MMF vs. NMF. Indeed, a recent study has reported that adding a single set to MMF to a NMF RT program may induce significantly greater strength and hypertrophic adaptations highlighting why this may be a limitation (Aguiar et al., 2015). Folland et al. (2002) required participants perform either 4 sets of 10 repetitions at 75% 1 repetition maximum (RM) with 30 seconds rest between sets to a group performing 40 single repetitions with 30 seconds rest between repetitions. However, whilst the use of inter-set rest periods is a common design for this research area, this protocol equates to 19 minutes and 30 seconds of rest between repetitions, which for only one exercise seems an impractical way to perform RT. Perhaps more importantly none

¹ The use of a protocol which requires maximal speed is effectively the same as training to MMF with regard to MU recruitment since intent and thus effort are likely maximal and in addition the muscular tension at peak velocity and peak force are likely similar (Behm & Sale, 1993).
of the studies comparing MMF to NMF reported any assessment of MU recruitment or intensity of effort level. This leaves us ignorant to what degree of effort was performed within these studies.

One recent study has attempted to compare training to MMF with training NMF when work was equated by attempting to control effort between groups through specific definitions of repetition cessation. Using trained participants Giessing et al. (2014) required one group to perform repetitions to a self-determined RM (described as participants stopping when they felt their next attempted repetition would result in MMF i.e. one perceived repetition short of MMF) and another group to actually train to MMF. They reported significant strength gains for the group training to MMF, however, the group training to self-determined RM did not significantly improve in strength. They speculated that this may be due to participants in the self-determined RM group being further from MMF than expected as other research has reported even experienced trainees under predict the number of repetitions possible before achieving MMF (Hackett et al. 2012).

Though the present body of literature and our understanding of the size principle might appear to support training to MMF it is still unknown the precise role, and to what degree, effort specifically plays in determining strength adaptations. It has been reported (Giessing et al. 2014) that low volume training (i.e. single set RT) may be dependent upon sufficient intensity of effort through training to MMF whereas RT involving higher volumes yet performed not to muscular failure (NMF) may result in a sufficient intensity of effort through cumulative fatigue across sets (Willardson, 2007). For example, a commercial method of training known as 5x5 (Starr, 1978) involving the performance of 5 sets of 5

---

2 Physiological effort is generally reported as a value from the rating of perceived exertion (RPE) scale. Previous application of this approach has been considered within the discussion section.
repetitions using ~80%1RM permits trainees to avoid training to MMF yet to accumulate a relatively high work volume. However, there appears to be no research examining this training method. Marshall et al. (2012) have acutely examined the effects of training involving 5 sets of 4 repetitions using 80%1RM using different rest periods with performing the same volume through consecutive sets to MMF. They reported greater electromyography amplitudes, and from this inferred higher MU activation, for the group training to MMF despite similar degrees of post exercise force reduction suggesting that it may offer a more efficacious training method, however, RPE was not reported.

Previous research does not fully elucidate the role of intensity of effort and its relationship to volume in determining training adaptations due to noted methodological limitations. A further potential confounding factor is between participant variations in response. It is known that there is a large heterogeneity in response to RT (Hubal et al. 2005) and thus the use of within subject designs could offer a more rigorous test of the role of intensity of effort and training to MMF. To date no previous studies appear to have compared load and volume equated unilateral training NMF with MMF. With this in mind the present study aimed to compare the effects of 6 weeks load-, volume- and repetition duration-equated, unilateral knee extension exercise to MMF or NMF using a 5x5 method including the use of a exertion\(^3\) scale to expand our understanding of this relationship.

**Methods**

**Study Design**

\(^3\) The terms ‘effort’ and ‘exertion’ have recently been discussed in detail (Abbis, et al. 2015) identifying that they might differentiate in meaning, however it is not within the scope of the present piece to consider similarities or differences and/or appropriation of terminology. The present piece uses the term ‘effort’ other than in reference to a specific named scale (e.g. RPE; rating of perceived exertion).
The present study aimed to compare the effects of a 6-week unilateral knee extensor RT programme using identical training loads, volumes and repetition duration performed to MMF or NMF using a 5x5 method. To avoid bias as a result of individual responses to training, we used a within-subject research design, where participants trained one leg to MMF and the contralateral leg to NMF. This methodological approach is well represented in previous research (e.g. Alegre et al. 2014; Fisher & Langford, 2014) and allowed for control of between participant confounding factors. Both legs were trained in the same session for the 6-week duration, alternating the leg which was exercised first (e.g. MMF or NMF) to nullify any effect of continued central fatigue.

Participants

An *a priori* power analysis of effect sizes for change in strength was conducted using effect sizes from recent meta-analysis of RT research (Fröhlich et al. 2010) to determine participant numbers (n) using effect size (ES) calculated using Cohen’s *d* (Cohen, 1992) of ~1.1-1.3 for improvements in strength. Participant numbers were calculated using G*Power* (Faul et al. 2007; Faul et al. 2009). These calculations showed that each group within the studies conducted required 6 to 7 participants to meet the required power of 0.8 at an alpha value of *p < 0.05* for the statistical analyses proposed (see below). Thus 6 was taken as the minimum participant requirement for the studies primary outcomes of change in strength. Attempts were made to recruit a greater number of participants considering attrition rates of ~50%.

Following approval from the relevant ethics committee (approval code: HESS#155), 9 recreationally active males were recruited from health and exercise science undergraduate degree courses (see Table 1 for participant characteristics). All participants had previous RT
experience but had not been engaged in a structured programme (e.g. >2 x / week) for the previous 6 months. All participants completed a physical activity readiness questionnaire (PARQ) and informed consent, and confirmed they were not using performance enhancing, or any other medication which might affect the study and were free from injury.

*INSERT TABLE 1 AROUND HERE*

**Testing Procedures**

All participants attended a familiarisation session where they performed a testing session in the exact format described below. This was to reduce any training effect of the tests pre- and post-intervention. Maximal voluntary isometric knee extension torque was measured unilaterally using a MedX knee extension/flexion dynamometer (MedX Corporation, Ocala, Florida) pre- and post-intervention. The final testing session was performed not less than 72 hours following the final training session to allow adequate recovery. The methods used have been described previously (Starkey et al. 1996; Fisher & Langford, 2014). However, succinctly; following a dynamic unilateral warm-up at 40lbs/~18kgs using a 2-s concentric, 1-s isometric pause, and 2-s eccentric repetition duration, participants performed three practice unilateral isometric tests at an estimated 50% of maximal effort. Each participant then performed maximal unilateral isometric tests at seven joint angles throughout the range of motion (102°, 96°, 78°, 60°, 42°, 24° and 18° of knee flexion). For each maximal isometric contraction participants were requested to build up to maximal force over 2–3 s and were provided with ~10 s rest between test angles. Following testing participants were asked to identify their dominant and non-dominant leg for assignment in to NMF and MMF training groups, respectively.

**Training Intervention**
Unilateral knee extension training was performed 2 x / week for 6 weeks (with no less than 48 hours between sessions) at 80% of maximal tested functional torque (TFT) on the same MedX device used in testing. For the MMF protocol all participants performed 25 repetitions with their non-dominant leg in the smallest number of sets possible, ensuring MMF was reached before cessation of each set (with the exception of the final set). Participants were required to attempt an additional repetition even when they felt it could not be completed, to ensure that MMF was reached. In a practical sense this meant that the MMF training always ended with an inability to complete a repetition. Repetition duration was controlled at 2-s concentric, 1-s isometric, 2-s eccentric as per the warm-up protocol. The MedX equipment is fitted with a sound to confirm completion of each repetition to ensure full range of motion. At the cessation of each set participants were required to report perceived effort from the Borg 15-point RPE scale (Borg, 1982). It was explained to participants that a rating of 20 on the RPE scale constituted maximal effort (i.e. MMF). Participants were provided 2 minutes rest between exercise sets.

For the NMF protocol, participants performed 5 sets of 5 repetitions (Starr, 1978) at the same repetition duration, and load as the MMF training protocol with their dominant leg. Upon completion of each set, each participant was again required to report effort from the Borg 15-point RPE scale, and then provided the same 2 minute rest between sets. Two minutes has been shown to allow sufficient ATP restoration to perform additional volume at the same loading (McMahon and Jenkins, 2002; Baechle and Earle, 2008). The loading remained constant throughout the intervention.

Statistical Analysis
Isometric force data was considered as a strength index (SI) provided by MedX clinical equipment. This has been reported previously (Fisher and Langford, 2014; Fisher, et al 2013) where SI represents the area under a force curve created in each isometric test and accommodates potential increases or decreases throughout the entire strength curve for all seven test positions. This negates biasing data by seeking average increases or decreases or only considering specific joint angles. The independent variable considered was the training condition (MMF or NMF) and the dependent variables included pre-strength, the absolute change in strength due to the intervention, average RPE across each set (averaged across the training intervention), peak RPE (averaged across the training intervention) and session duration for each protocol (averaged across the training intervention and including time to perform repetitions and rest time).

A Kolmogorov-Smirnov test was conducted to examine whether data met assumptions of normality of distribution. Where assumptions of normality were met paired samples t-tests were used to compare within participants across the independent conditions (MMF vs. NMF). In addition, repeated measures analysis of variance with a Greenhouse-Geisser adjustment when assumptions of sphericity were violated was used to examine the effect of the factor ‘set’ upon RPE in the NMF condition. Where a significant effect by ‘set’ was found post hoc pairwise comparisons with a Bonferonni procedure were conducted to examine differences between sets. All data were considered continuous and so met assumptions for parametric testing including RPE using the 15-point scale which has been supported as producing interval data (Borg, 1998).

Statistical analysis was performed using IBM SPSS Statistics for Windows (version 20; IBM Corp., Portsmouth, Hampshire, UK) and \( p \leq 0.05 \) set as the limit for statistical significance.
Further, 95% confidence intervals (CI) were calculated to examine significance for within-condition changes in absolute strength (where a change was considered significant if the 95%CIs did not cross zero) in addition to ES using Cohen’s *d* (1992) for absolute change in strength for each condition, and differences between conditions for average RPE and peak RPE, to compare the magnitude of effects between conditions where an ES of 0.20-0.49 was considered as small, 0.50-0.79 as moderate and ≥0.80 as large.

**Results**

**Strength**

Paired samples t-test revealed no significant difference between MMF and NMF for baseline strength (*t*(8) = 1.035, *p* = 0.331; MMF = 10948 ±1910 vs. NMF = 11348 ±1697) and absolute change in strength (*t*(8) = -1.199, *p* = 0.265). ESs for absolute changes in strength within conditions were considered large for both (MMF = 2.01 and NMF = 1.65) and 95%CIs suggested both conditions resulted in significant strength gains. Figure 1 shows absolute change in strength for both conditions with 95%CIs. The 95%CIs for change in absolute strength revealed that both conditions experienced a significant within-condition improvement.

*INSERT FIGURE 1 AROUND HERE*

**Rating of Perceived Exertion**

Paired samples t-test revealed a significant difference between MMF and NMF for both average RPE (*t*(8) = 16.835, *p* < 0.0001; 95%CIs 4.21 to 5.55) and peak RPE (*t*(8) = 8.859, *p* < 0.0001; 95%CIs 3.47 to 5.90). ESs for differences between conditions were considered large for both average RPE (5.61) and peak RPE (2.95). Table 2 shows average RPE and peak
RPE for both conditions. Repeated measures analysis of variance found a significant effect by ‘set’ for RPE for the NMF group ($F_{(1.142, 28.508)} = 13.344, \ p = 0.004$). Pairwise comparisons revealed that set 1 differed significantly from set 5 ($p = 0.047$), set 2 differed significantly from set 5 ($p = 0.040$), set 3 differed significantly from sets 4 ($p = 0.044$) and 5 ($p = 0.013$), and set 4 differed significantly from set 5 ($p = 0.018$). Figure 2 shows RPE by set for NMF in addition to MMF for comparison.

*INSERT TABLE 2 AROUND HERE*

*INSERT FIGURE 2 AROUND HERE*

**Session Duration**

The MMF condition required 3.35±0.70 sets to complete the 25 repetitions. Paired t-test revealed a significant difference between MMF and NMF for session duration ($t_{(8)} = -9.323, \ p < 0.001$). Average session duration for the MMF condition was 425.67±97.93 seconds (~7 minutes and 6 seconds) compared with 720 seconds (12 minutes and 10 seconds) for NMF.

**Discussion**

The aims of the present study were to compare training to momentary muscular failure (MMF) and not to muscular failure (NMF) with load and volume equated, something which had previously not been presented in the literature. In doing so we also tested the efficacy of the commercialised ‘5x5’ training programme originally proposed by the recently deceased Bill Starr (1978). Using a within subject research design recreationally active male participants performed a unilateral knee extension exercise to MMF and NMF using their non-dominant and dominant legs respectively.
Pre-intervention isometric testing revealed no statistically significant differences between dominant and non-dominant leg. Following 2 x / week unilateral knee extension training for 6 weeks, both interventions showed significant increases in maximal isometric force as indicated by 95% CIs (Figure 1). Mean (±SD) values for SI increased for both groups; MMF: pre = 10948 ±1910, post = 15964 ±2528 (~46%) and NMF: pre = 11348 ±1697, post = 15917 ±2808 (~40%). Despite analyses revealing no significant differences in absolute change in strength between groups it should be noted that ESs were greater in the MMF condition compared with the NMF condition (2.01 and 1.65 for MMF and NMF respectively). Previous research has been equivocal in nature where some authors have reported more favourable adaptations following training to MMF (Rooney et al. 1994; Schott et al. 1995; Drinkwater et al. 2005; Giessing et al. 2014) whilst other authors have reported comparable results (Izquierdo et al. 2006; Folland et al. 2002; Sampson & Groeller, 2015). However, multiple limitations of this existing body of research have restricted the extent to which these conclusions can be considered. For example; velocity of contraction (Izquierdo et al. 2006), performance of maximal exercise sets in both groups to determine training load (Sampson & Groeller, 2015) and impractical training approaches (Folland et al. 2002) limit our confidence and application of this research area. The present study addresses many of these limitations and supports previous studies suggesting there are likely no significant differences in strength adaptations between resistance training to MMF and NMF in untrained persons.

Research has previously suggested the use of rating of perceived exertion scales (RPE; see Morishita et al. 2013 for a review) to quantify intensity of effort. However, once again methodological issues limit the application of these resources. For example Gearhardt Jnr et al. (2002) reported lower RPE values for participants performing 15 repetitions at 30%
1RM compared to those performing 5 repetitions at 90% 1RM. Initially it appears logical that a heavier load might equate to a higher degree of effort and indeed, recent research has shown that, when work volume matched, heavier loads result in higher RPE values. However, when sets are performed to MMF RPE is similar irrespective of other variables (Hiscock et al. 2015). Nevertheless a lack of parity in volume complicates this issue. Previous research has suggested that 5 repetitions at 90% of 1RM is closer to MMF (and thus equates to a higher intensity of effort) than 15 repetitions at 30% of 1RM (Shimano et al. 2006; Hoeger et al. 1990). Thus, as discussed previously (Fisher et al. 2011), this represents the most common misconception; that load x repetitions = intensity of effort. Perhaps the most valuable of studies considering subjective rating of exertion is that of Shimano et al. (2006) who considered RPE values in trained and untrained males performing a single set to failure at 60%, 80% and 90% 1RM for back squat, bench press and arm curl. The authors reported no significant differences in RPE between load and exercise performed, with the exception of significantly higher exertion values for the back squat at 60% 1RM in trained persons (8.8 ±0.7 vs. 6.9 ±1.9). This suggests that the volume of repetitions preceding MMF may have incurred a greater degree of discomfort resulting in a higher RPE value. We have quite specifically termed this discomfort rather than exertion for the following reason. The authors reported that participants exercised to muscular failure with verbal encouragement to ensure adequate motivation and effort, and RPE was measured using a Borg CR10 scale (Borg, 1982), where a value of 10 indicates maximal effort. In this case, each trial, irrespective of exercise, load, or training status should have resulted in a maximal value for effort since participants were exercising to MMF. Since participants did not report maximal values we can only assume that the participants were unclear as to how to report their feelings of effort, and more likely expressed their feelings of discomfort.
Within the present research design participants reported RPE following each exercise set. As one might expect, analyses revealed significantly higher mean and peak RPE values for the MMF exercise sessions compared to NMF (see Table 2 for values). Since the MMF condition reported higher RPE values but failed to increase strength beyond that of the NMF condition we might consider that for recreationally active (but non-resistance trained) persons there may be a threshold to adaptive responses to RT, but that beyond this threshold greater intensity of effort is unnecessary and results in diminishing magnitude of adaptations undetectable with the present sample size and analysis (e.g. $p > 0.05$).

Henneman’s size principle states that as smaller, lower threshold MUs fatigue so larger, higher threshold MUs are recruited. It seems likely that performance of multiple sets of an exercise with a minimal load and insufficient rest can incur a cumulative fatigue of muscle fibers and MUs incurring the recruitment of higher threshold MUs for adaptation. Previous research supporting similar adaptations between MMF and NMF have considered recreationally active participants and whilst they failed to consider RPE their respective protocols support this threshold hypothesis (Izquierdo et al. 2006; Folland et al. 2002; Sampson & Groeller, 2015). It could however be suggested that, practically speaking and considering prior research shows poor ability to estimate proximity to MMF even in trained adults (Hackett et al. 2013; Giessing et al. 2014), that it may still be desirable to attempt to train to MMF with untrained recreationally active people. This might ensure that a threshold for optimising adaptations has been met.

In contrast to studies of untrained people some of the previous research, which has suggested greater adaptations as a result of RT to MMF, have considered participants with previous RT experience (Drinkwater et al. 2005; Giessing et al. 2014) which might require greater stimulus or a higher threshold of effort to catalyse adaptation. Where protocols
found favourable results for RT to MMF and considered participants without previous RT experience, it might be that subjects within MMF training groups simply made greater adaptations to the MMF RT protocol compared to those within NMF groups, potentially due to a larger rest period in the NMF groups preventing complete recruitment of the higher threshold MUs (Rooney et al. 1994; Schott et al. 1995).

Since the present study considered a unilateral training protocol it represents the first research study in this area which has adequately controlled for nutrition, sleep patterns, genetics and hormonal responses to RT protocols. However, the use of a within-participants, unilateral RT protocol is not without limitations which should be discussed. Whilst this methodological approach adequately controls the aforementioned variables, we should consider that there might be chronic neural adaptations resulting from cross-education which could have impacted our results and limit the extent of our conclusions. Indeed meta-analysis of the cross-educational effect of unilateral training have suggested it contributes 7.8% absolute strength increase to the contralateral limb (Munn et al., 2004). However, this adaptation is hypothesised to result from neural mechanisms involving facilitation of an untrained contralateral motor cortex following excitation of a trained limb. As such, it could be argued that with our within subjects design (where both limbs were trained) would have therefore controlled for this degree of improvement between limbs and any difference in strength gains or lack thereof would be due to the training conditions.

In addition, the cause of failure with different repetition ranges may differ. Behm et al. (2002) found that MMF occurred in low rep (5) sets due to more centrally mediated fatigue whereas higher rep sets (20) were more mainly due to peripheral neuromuscular mediated fatigue. Thus depending on the number of sets performed to MMF there may be
differential degrees of centrally stimulated adaptations and cross-educational effects. The MMF condition performed 12.31±2.29 repetitions in the first set and so the effects of central fatigue may not have been so severe. However, despite these factors, it is currently unknown as to whether contralateral adaptations over a training intervention do indeed differ when the ipsilateral limb has been trained to MMF or NMF and as such this limitation should still be considered. Ultimately almost all RT research will be limited either by between group differences which are not controlled or said limitations of a within group design. The present study appears the first to consider a within-participant design in the area of MMF vs. NMF RT.

It is also feasible that training to MMF may impart greater adaptations in a contralateral limb due to potentially greater stimulus of centrally mediated neural factors through non local muscular fatigue (NLMF; Halperin et al., 2015). Whilst it is not within the scope of this article to provide extensive discussion, in brief; NLMF indicates a deficit in acute muscular performance in unexercised muscles as a result of exercising other (including contralateral) muscle groups (see Halperin et al, 2015 for a comprehensive review). In context, NLMF might have resulted in the NMF limb equating to a higher degree of fatigue (potentially as a result of MU recruitment and muscle fibre activation) when performed subsequent to the MMF limb. Whilst we alternated priority of MMF and NMF training protocols each session aiming to avoid systemic fatigue affecting results, we should consider that this is a complex area with equivocal results relating to intensity of effort and regarding contralateral force production and maximal force contraction time (Halperin, et al. 2015). In review Halperin et al. (2015) specifically noted that NLMF appears to be more prevalent in the knee extensors and may be impacted more by prolonged repetitive
contractions (such as training to MMF) and as such, in the present study, each unilateral exercise session might have induced a degree of contralateral fatigue.

In context another potential limitation of the present study was the lack of randomization for dominance/non-dominance of leg in to MMF and NMF groups. Considering the present sample size we felt that potentially dividing groups by another level (e.g. dominant and MMF, non-dominant and MMF, dominant and NMF, non-dominant and NMF) was unsuitable. In the context of our findings however this would seem to have been a minimally confounding factor. Training the dominant limb may have a greater impact on strength gains in the contralateral limb than the effect of training the non-dominant limb (Farthing, 2009). Thus our study design may in fact have favoured greater strength gains in the NMF condition. Our results, though non-significant, contrastingly revealed a greater ES within the MMF condition. Thus, despite meeting our sample size estimations for adequate power, it is possible that a type II error resulted. Future investigators should consider this factor in the design of studies.

Finally we should consider the efficiency and practicality between training interventions. The MMF protocol required ~7 minutes and 6 seconds to complete, whereas the NMF 5x5 protocol required 12 minutes and 10 seconds to complete. This equates to ~40% greater time for the NMF group which if extrapolated to consider multiple exercise protocols would require ~80 minutes and ~120 minutes for MMF, and NMF respectively for 10 exercises using the same volume equated protocol. If statistically similar (or possibly greater based on ESs) strength gains are attainable in a shorter time then we might consider the MMF protocol far more time efficient and practically viable.

**Practical applications**
The present research suggests that, when training to NMF using a 5x5 approach, untrained people may attain similar strength increases when compared to training to MMF. This has application for people beginning or returning to a strength training programme to provide a larger volume which might allow individuals to practice the skill of technical movements and gain confidence in their exercise protocol. In addition the use of 5x5 training NMF might help adherence for those beginning exercise programmes or people with symptomatic conditions which might prevent them from exercising at the high levels of discomfort associated with MMF. Future research should consider whether hypertrophic and health related adaptations are also similar between NMF using a 5x5 protocol and MMF training protocols. Coaches should consider using this research to support their exercise prescriptions in novice or untrained athletes wishing to develop strength, or in the periodization of trained athletes to prevent overtraining. In this sense NMF training might have application for the maintenance of strength in subsidiary musculature (e.g. to maintain upper body strength in endurance cyclists) without the physiological stresses associated with training to MMF. Conversely, programming some sessions to include training performed to MMF may offer slightly greater strength gains and it may positively affect fatigue resistance through improved mental toughness due to the high effort involved (Marcora et al., 2009). However, the present study supports that training to MMF appears a far more time-efficient RT protocol.

**Conflicts of Interest**

The authors have no conflicts of interest to declare.
References


Hubal, M.J., Gordish-Dressman, H., Thompson, P.D., Price, T.B., Hoffman, E.P.,
Angelopoulos, T.J., Gordon, P.M., Moyna, N.M., Pescatello, L.S., Visich, P.S., Zoeller, R.F.,
Seip, R.L., and Clarkson, P.M. 2005. Variability in muscle size and strength gain after

Izquierdo M., Ibañez, J., González-Badillo, J.J., Häkkinen, K., Ratamess, N.A., Kraemer,
Differential effects of strength training to failure versus not to failure on hormonal
responses, strength and muscle power increases. J. Appl. Physiol. 100: 1647-56.

Marcora, S.M., Staiano, W., Manning, V. 2009. Mental fatigue impairs physical

153-158.

McMahon, S., and Jenkins, D. 2002. Factors affecting the rate of phosphocreatine

Morishita, S., Yamauchi. S., Fujisawa, C., and Domen, K. 2013. Rating of perceived
Rehab. 1(9): 172.

resistance training: a meta-analysis. J. Appl. Physiol. 96(5): 1861-1866

Newman, A.B., Kupelian, V., Visser, M., Simonsick, E.M., Goodpaster, B.H., Kritchevsky,
S.B., Tylavsky, F.A., Rubin, S.M., and Harris, T.B. 2006. Strength, but not muscle mass, is


Table 1. Participant Characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>(Mean ± SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>21.4 ± 1.2</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>179.2 ± 6.7</td>
</tr>
<tr>
<td>Body mass (kg)</td>
<td>78.4 ± 7.1</td>
</tr>
<tr>
<td>BMI (Kg.m^2)</td>
<td>24.4 ± 1.8</td>
</tr>
</tbody>
</table>
Table 2. Average RPE and peak RPE

<table>
<thead>
<tr>
<th></th>
<th>MMF</th>
<th>NMF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average RPE*</td>
<td>18.8±0.6</td>
<td>13.9±1.1</td>
</tr>
<tr>
<td>Peak RPE*</td>
<td>20.0±0.1</td>
<td>15.3±1.6</td>
</tr>
</tbody>
</table>

Note: Mean ±SD; * indicates significant difference between conditions
Figure Captions

Figure 1. Mean absolute change in strength with 95%CIs for both MMF and NMF

Figure 2. RPE across sets (mean ±SD).