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1 **High- and Low-load resistance training; Interpretation and Practical Application of**

2 **Current Research findings**

3

4 Current Opinion

5

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26 **Key Points**

27 Current research is equivocal regarding the use of heavy- or light-loads for optimal strength
28 and hypertrophic adaptations.

29 Misinterpretation of EMG amplitude, differing hypertrophic assessment methods (e.g. *in vivo*
30 and *in vitro*) and unconsidered motor schema research might present reasons behind the
31 differing adaptations reported.

32 **Abstract**

33 Our current state of knowledge regarding the load (lighter or heavier) lifted in resistance
34 training programs to result in 'optimal' strength and hypertrophic adaptations is unclear.

35 Despite this, position stands and recommendations are made based on, we propose, limited
36 evidence to lift heavier weights. Here we discuss the state of evidence on the impact of load
37 and how it, as a single variable, stimulates adaptations to take place and whether evidence for
38 recommending heavier loads is available, well defined, currently correctly interpreted, or has
39 been overlooked. Areas of discussion include electromyography amplitude, *in vivo* and *in*
40 *vitro* methods of measuring hypertrophy, and motor schema and skill acquisition. The present
41 piece clarifies to trainers and trainees the impact of these variables by discussing
42 interpretation of synchronous and sequential motor unit recruitment and revisiting the size
43 principle, poor agreement between whole muscle cross sectional area (CSA) and biopsy
44 determined changes in myofibril CSA, and neural adaptations around task specificity. Our
45 opinion is that the practical implications of being able to self-select external load might
46 reduce the need for specific facility memberships, motivate older persons or those who might
47 be less confident using heavy loads, and allow people to undertake home- or field-based
48 resistance training intervention strategies which might ultimately improve exercise
49 adherence.

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53 **1. Introduction**

54 The role of load within resistance training is presently a hotly discussed topic in
55 exercise science. Recent reviews have examined existing studies comparing the effects of
56 different loads upon muscle function (e.g. strength and endurance) and hypertrophy. In these
57 reviews some authors have suggested that, when resistance training is continued to
58 momentary failure, essentially the same adaptations are possible with both heavy-(HL) or
59 light-loads (LL) [1,2]. In contrast, others suggest that inclusion of specifically LL or HL may
60 be necessary for optimising certain adaptations [3-6]. We propose that ‘heavy’ and ‘light’
61 loading systems exist on a spectrum and are individual based on subjectivity, however, for
62 clarity, HL and LL have been operationally defined as >65% 1-repetition maximum (RM)
63 and <60% 1RM, respectively [6]. A number of recent studies have been published examining
64 both acute mechanistic differences resulting from difference in load in addition to studies
65 comparing chronic changes in muscle function and hypertrophy. Unfortunately, we believe
66 that some researchers may have inappropriately interpreted the data produced in these
67 studies, with much of this surrounding incorrect inferences regarding motor unit (MU)
68 recruitment in acute studies of electromyography (EMG), in addition to different methods of
69 measuring both muscle function and hypertrophy. With this in mind, in the present piece we
70 aim to discuss why different exercise scientists might have given contrasting
71 recommendations by discussing the factors that should be considered in interpretation of
72 research within this area.

73 **2. Acute EMG Amplitude and the Size Principle**

74 It is commonly accepted within the resistance training literature that recruitment of a
75 MU is necessary in order for subsequent adaptation to occur [7]. Since discussions around
76 optimal load for muscular adaptations are predicated upon the belief that complete

77 recruitment of MUs and thus muscle fibres is required for optimal adaptations, it is essential
78 to consider acute EMG research within this area as well as briefly reconsider the size
79 principle of motor unit recruitment. Recent studies have reported higher peak EMG
80 amplitude for HL compared with LL [7,8] with one recent study showing increasing EMG
81 amplitudes from 50% to 70% and to 90% 1RM [9]. From this the authors of these studies
82 have inferred that LL do not maximally recruit all MU and as such HL are favourable for
83 development of strength and hypertrophy. However, such recommendations may be founded
84 upon an incorrect use and interpretation of EMG data relating to MU recruitment as well as a
85 misapplication of the size principle.

86 For clarity, the size principle states that *“when the central nervous system recruits*
87 *motor units for a specific activity it begins with the smallest, more easily excited, least*
88 *powerful motor units and progresses to the larger, more difficult to excite, most powerful*
89 *motor units to maintain or increase force”* [10,11]. However, as noted recently by Enoka and
90 Duchateau [12], whilst EMG amplitude is influenced by MU recruitment strategies many
91 continue to mistakenly infer MU recruitment from amplitude data. For example during a
92 maximal voluntary contraction more MUs, including both those of a low or high threshold,
93 will be activated and at increased frequencies in order to produce maximal force. As such the
94 high MU recruitment would result in a higher EMG amplitude. In comparison, a sustained
95 submaximal contraction would only recruit sufficient MUs to produce the necessary force;
96 however, as those MUs fatigue other MUs would be recruited to replace them in sustaining
97 the desired force. Indeed, during fatiguing contractions the threshold for recruitment of higher
98 threshold MU is reduced permitting their subsequent recruitment [13] and MUs may ‘cycle’
99 (momentary de-recruitment and recruitment of different MU) during submaximal fatiguing
100 contractions to reduce fatigue and maintain force [14]. Furthermore the ‘muscle wisdom
101 hypothesis’ suggests that during sustained contractions motor unit discharge rate might

102 decrease due to optimizing the force output of motor units and protecting against peripheral
103 conduction failure (Petrofsky & Phillips, 1985; Behm, 2004). Should this decrease in
104 discharge rate occur, there would be a resultant decrease in signal amplitude (Garland &
105 Gossen, 2002). As such, whilst HL would require more synchronous MU recruitment at
106 greater frequencies (resulting in higher EMG amplitudes), sustained contractions to muscular
107 failure with LL might ultimately recruit all MUs albeit sequentially (resulting in lower EMG
108 amplitudes) rather than synchronously.

109 It should be noted that whether MU recruitment is ultimately similar between HL and
110 LL remains a hypothesis to test empirically. Examination of this would require more
111 advanced handling of EMG data such as spike-triggered averaging [15] or initial wavelet
112 analysis followed by principal component classification of major frequency properties and
113 optimization to tune wavelets to these frequencies [16]. Though acute mechanistic data
114 cannot be used to infer chronic adaptations, studies such as these recent EMG amplitude
115 comparisons of HL and LL are useful for generating hypotheses for examination in chronic
116 training interventions. However, the hypotheses presented by the authors of these recent
117 studies suggesting that HL may produce greater adaptations appear to stem from
118 inappropriate interpretation of EMG amplitudes and consideration of the size principle.

119 **3. Hypertrophic Adaptations**

120 Common methods of measuring hypertrophy are *in vivo* (e.g. computed tomography
121 [CT], magnetic resonance imaging [MRI] and ultrasound [UT]) and *in vitro* (e.g. muscle
122 biopsy). Recent reviews have differed in their inclusion of studies using these methods with
123 some opting to examine only *in vivo* measures of whole muscle hypertrophy [1] and others
124 considering both *in vivo* and *in vitro* measures [5,6]. In fact, methods used to measure
125 hypertrophy, the information they can provide and the strengths and weaknesses of both have

126 been discussed in light of these publications [17,18]. We acknowledge that whilst both *in vivo*
127 and *in vitro* methods present useful information both offer very different information and that
128 the two should be interpreted individually and carefully.

129 In both a recent review [5] and meta-analysis [6] of hypertrophy in response to HL
130 and LL, resistance training studies utilising both muscle biopsy and *in vivo* methods were
131 considered, and in the meta-analysis combined for analysis. The combination of *in vivo* and
132 *in vitro* measures in this meta-analysis might have confounded the overall conclusions drawn
133 in relation to other publications [1]. In support of this concern, a study by Mitchell et al. [19]
134 included in the meta-analysis conducted both MRI and biopsy measures of hypertrophy in
135 response to different resistance training loads and reported that relative increases appear
136 greater for biopsy measures (mean = ~17-30% type I and ~16-18% type II; favouring low and
137 high load conditions respectively in terms of effect size) compared to MRI (~7%; favouring
138 the high load condition in terms of effect size). McCall et al. [20] have also reported
139 differences between muscle biopsy and MRI methods in magnitude of CSA increase (mean
140 =; biopsy = 10% type I fibre and 17% type II vs. 11.2% MRI). It is not clear from the meta-
141 analysis method section how the authors dealt with the inclusion of the different outcome
142 measures for hypertrophy used by Mitchell et al. [19], i.e. whether they were dealt with
143 separately or combined. Indeed it has been noted [17] that in the earlier review [5] those
144 studies using *in vivo* measures of whole muscle hypertrophy consistently showed no
145 difference between HL and LL whereas the two *in vitro* studies using biopsies did show
146 significantly greater gains for HL. Whilst ultimately still not statistically significant
147 ($p=0.076$), it is unclear the degree to which the combination of methods influenced the results
148 of this meta-analysis in favour of greater ESs for HL compared to LL ((mean \pm SD) LL= 0.39
149 \pm 0.17; HL= 0.82 \pm 0.17). Figure 1 shows an adaptation of the forest plot originally published
150 by Schoenfeld, et al. [6]. The dotted line shows the overall ES and clearly shows studies

151 which considered *in vivo* methods to the left of the dotted line, and studies which considered
152 *in vitro* methods to the right of the line, which we propose might have contaminated the
153 analyses and overall outcome.

154 The use of *in vitro* measures such as muscle biopsy permits the examination of many
155 important aspects of muscular adaptation including individual fibre typing, individual fibre
156 area, mitochondrial content, enzyme expression, capillarisation. Indeed it has been suggested
157 that fibre type specific adaptations may occur in response to HL or LL training [21] and,
158 though evidence is mixed at present as to whether this indeed occurs [19,22,23], biopsy
159 would be necessary to test this hypothesis further. Pertinent to hypertrophy as an outcome it
160 has been argued that a case could be made for biopsy providing the most relevant information,
161 as individual fibre area can be determined, thus allowing differentiation between contractile
162 and non-contractile components [5]. However, it should be noted that evidence is equivocal
163 regarding the agreement between whole muscle CSA changes and biopsy-determined
164 changes in myofibril CSA, with some studies suggesting similar magnitude of relative change
165 [24,25] whereas others do not [26,27]. In fact, authors have actually agreed that “*it might be*
166 *true...that single fiber CSA data over-estimate whole muscle CSA*” [Burd, et al. 2013;
167 Schuenke, et al. 2013]. Methods exist to ensure sufficient tissue samples are obtained for
168 analysis using biopsy, yet, only a limited number of cells are assessed irrespective of method.
169 In this sense, variation in fibre characteristics and non-uniform growth along the length of a
170 muscle [28] provide notable limitations in attempting to extrapolate biopsy results to consider
171 whole muscle change [29]. However, measuring muscular adaptation using *in vivo* methods is
172 not without issues: different methods (MRI, CT, UT) can offer different information for both
173 individual and whole muscle groups including CSA, muscle thickness, muscle density,
174 architectural changes such as pennation angle, and changes in non-contractile components
175 such as intra-muscular adipose tissue. Again pertinent to the outcome of hypertrophy, even

176 consideration of whole muscle changes in CSA or muscle thickness may not be fully
177 reflective of morphological adaptation. CSA may also include non-contractile components
178 and so increases may not fully reflect muscular adaptations. Further and conversely, prior
179 studies have reported lack of change in CSA yet significant increases in muscular density
180 [30] in addition to disproportionate strength and CSA gains possibly being influenced by
181 changes in muscle density [31].

182 In our opinion, the confounding factors discussed limit the integrity of any outcome
183 data where analyses have combined these methods of measurement of hypertrophy.
184 Furthermore, from a practical perspective, different outcomes may hold different value for
185 persons with different goals. For example, those with aesthetic goals may have greater
186 interest in whole muscle changes irrespective of whether changes occur as a result of
187 contractile or non-contractile components increasing, whereas those with more performance-
188 specific goals may have greater interest in fibre-specific adaptations or changes in muscle
189 density. As such we believe that the different outcome methods, though both providing
190 important information, ultimately provide different information and should be considered as
191 such in interpretation.

192 **4. Muscle Function Adaptations**

193 Muscle function is often measured as either strength, relative endurance (repetitions
194 performed at a submaximal %1RM load) or absolute endurance (repetitions performed with
195 an absolute submaximal load). The nature of testing mode for these can vary considerably
196 including free weights, resistance machines, and isokinetic or isometric dynamometers.
197 Publications from the American College of Sports Medicine (ACSM) have suggested that HL
198 promote greater strength adaptations whereas LL may promote greater endurance adaptations
199 (though it is not specified whether they refer to relative or absolute endurance) [3,4].

200 However, these claims have received criticism [32,33] and authors of more recent reviews
201 have reported similar increases in strength and absolute endurance adaptation irrespective of
202 training load [2,10,34]. The similar changes in strength and absolute endurance have been
203 suggested as possibly due to the inherent relationship between the two outcomes [35,36].
204 With this in mind it is important to consider the nature of the measures of muscular function
205 employed in studies considering HL and LL training.

206 The recent meta-analysis referred to above [6] also examined a muscle function
207 outcome (strength), again reporting no significant difference between HL and LL but a
208 greater effect size in the HL condition ((mean \pm SD) LL= 1.23 \pm 0.43; HL= 2.30 \pm 0.43).
209 However, again some studies have utilised differing methods of measuring muscle function
210 within their designs. For example, Mitchell et al. [19] reported a number of different muscle
211 function related outcomes including strength (1RM and isometric maximal voluntary
212 contractions) and relative endurance (repetitions to failure with both 30%- and 80%1RM
213 loads in addition to total work). These varied with regards to whether changes significantly
214 favoured the HL group (1RM and total work with 80%1RM) or the LL group (number of
215 repetitions with 30%1RM). The authors of a more recent publication reported significantly
216 greater strength adaptations for the back squat, but not bench press, 1RM when using 70-80%
217 1RM compared to 30-50% 1RM (although larger ESs for bench press were noted for the
218 higher load group) [37]. Further, changes in relative endurance (repetitions to failure using
219 50%1RM) were significantly greater for the LL group. Interestingly, there were no significant
220 between-group (HL vs. LL) differences for hypertrophy of the elbow flexors, extensors and
221 quadriceps muscles. In contrast, the same group of authors reported significantly greater
222 increases in 1RM for bench press, but not back squat, when training with 3RM compared to
223 10RM [38]. Another paper included in the above noted meta-analysis (Ogasawara et al.,
224 2013) found no difference in elbow extension isokinetic strength between HL and LL groups

225 but did for bench 1RM. As with studies included in the hypertrophy component of this meta-
226 analysis it is not clear how different outcomes were handled for these studies [19; Ogasawara
227 et al. 2013] and, for reasons described below, this may have similarly impacted the ESs in
228 favour of HL conditions.

229 It is interesting to consider the reasons for the divergent results within these studies
230 and to consider the testing modes employed. We propose that one reason as to why there
231 might be differing strength and hypertrophic adaptations might be that of skill specificity in
232 motor recruitment (Behm & Sale, 1993). Motor control research suggests that a motor
233 schema is highly specific to the task being practised [39,40], and though it could be argued
234 that the higher number of repetitions associated with LL training could suggest a greater
235 volume of practice favouring those conditions, motor schemata have also been reported to be
236 *load/force* specific [41]. With this in mind, lifting a heavier load in a particular movement
237 might serve to practise and refine that schema as a skill which would include the maximal
238 synchronous recruitment of motor units and muscle fibres. This is a key reason why most
239 maximal testing protocols include some sort of familiarisation or practice component within
240 exercise science research [42]. Indeed the results of Mitchell et al. [19] support this
241 contention: though the HL group had a greater increase in 1RM, possibly due to the motor
242 schema refinement that likely occurred from training closer to their maximal load, there were
243 no differences between the HL and LL groups for peak isometric maximal voluntary
244 contraction, maximal power output, or rate of force development. The tendency for greater
245 strength gains in the HL groups in the studies by Schoenfeld et al. [37,38] may also be due to
246 this specificity of motor schema refinement. Further, the 1RM tasks measured were
247 compound free weight movements (squat and bench press) which have been shown to require
248 multiple (~3-5) familiarisation sessions even in moderately trained persons due to continued
249 increases in 1RM [43] and improvements during these are likely attributable to neural and

250 learning effects [44]. In support of this are the results from Ogasawara et al. (2013) who
251 reported significantly greater gains in bench press 1RM for the HL group however found no
252 differences between groups for elbow extension strength. Thus, in the studies mentioned the
253 apparent superiority of HL in enhancing strength may simply reflect better learning of the
254 specific skills involved in the testing. In contrast, more simple strength tasks such as
255 dynamometry of isolated joint movements require less refinement of motor schemata
256 evidenced by the requirement for only a single familiarisation session to achieve reliable
257 results [45,46]. However, that single familiarisation session is still essential to achieve valid
258 results and therefore even with such simple tasks there is clearly a skill learning element to
259 testing results. In our opinion researchers should therefore bear the specificity principle in
260 mind when comparing the results of different training protocols, as the similarity of training
261 and testing protocols is likely a key factor.

262

263 **5. Exertion and discomfort**

264 We also speculate that a secondary reason as to the differing results in these studies
265 [19,37,38], particularly with respect to the changes in relative endurance, may relate to
266 exertion and associated discomfort. The differentiation between perceptions of effort and
267 discomfort have been highlighted recently as important [47], particularly within RT [48], for
268 good reason.

269 Shimano et al. [49] considered rating of perceived exertion (RPE) values in trained
270 and untrained persons performing a single set to momentary failure at 60%, 80% and 90%
271 1RM for back squat, bench press and arm curl. The authors reported no significant
272 differences in RPE between load and exercise performed, with the exception of a
273 significantly higher exertion for the back squat at 60% 1RM in trained persons ((mean \pm SD)

274 8.8 \pm 0.7 vs. 6.9 \pm 1.9). This might suggest that the volume of repetitions preceding
275 momentary failure may have produced a greater degree of discomfort resulting in a higher
276 RPE value. Indeed further research has shown that when performing multiple sets to
277 momentary failure, mean (\pm SD) RPE increases significantly from set one (50%1RM =
278 7.40 \pm 1.96 vs. 70%1RM = 7.73 \pm 1.44), to two (50%1RM = 8.60 \pm 0.99 vs. 70%1RM =
279 8.73 \pm 0.80), to three (50%1RM = 9.33 \pm 0.82 vs. 70%1RM = 9.47 \pm 0.74) with no difference
280 between different loads [50]. We have quite specifically termed this discomfort rather than
281 exertion for the following reason. The authors of these studies reported that participants
282 exercised to momentary failure with verbal encouragement to ensure adequate motivation and
283 effort, and RPE was measured using a Borg CR10 scale [51], where a value of 10 indicates
284 maximal effort. In this case, each trial, irrespective of exercise, load, or training status should
285 have resulted in a maximal value for effort since persons were exercising to momentary
286 failure. Since participants did not report maximal values we can only assume that the
287 participants were unclear as to how to report their perception of effort, and as such,
288 potentially expressed their feelings of discomfort. Again, despite also using the Borg CR10
289 RPE scale and having participants train to momentary failure, Pritchett et al. [52] also
290 reported RPE values of less than 10 for both acute and session RPE. However, RPE was
291 significantly higher for the 60%1RM condition compared with 90%1RM, suggesting the LL
292 with a higher number of repetitions incurred a higher discomfort than training at a HL. Based
293 on this we hypothesise that people might find it more difficult to reach momentary failure
294 with a LL because of a higher discomfort. As such, studies comparing HL and LL training
295 where participants are said to have trained to momentary failure might be limited by a high
296 discomfort in the LL group, preventing participants from reaching true momentary failure.
297 We propose that in comparison of HL and LL groups the conduct of reaching momentary
298 failure becomes all the more important in a LL group to maximally, sequentially recruit all

299 possible motor units. However, we should acknowledge that at present there are insufficient
300 studies comparing LL training to momentary failure and not to momentary failure to
301 determine how much of a meaningful difference a final repetition (e.g. reaching ‘true’
302 momentary failure) might make towards chronic adaptations.

303 **6. Conclusion**

304 When considering the findings of studies comparing the effects of HL and LL, there
305 are a number of important factors to consider. These include the different outcomes related to
306 morphological changes providing differing information, skill associated with the testing
307 mode chosen (both load and task), and other psychosocial factors such as discomfort. We
308 contend that different testing modes evidently reflect different outcomes and indeed they may
309 hold different values for persons with different goals. Again it is possible that HL or LL may
310 favour certain outcomes and not impact upon others. For example, if solely wishing to
311 improve maximal strength of a specific task (such as a powerlifter wishing to improve back
312 squat, deadlift or bench press) a recommendation might be to perform these specific exercises
313 using heavy loads to attempt to catalyse both morphological and neural adaptations [30].
314 Whereas those more interested in improving muscular force production for health parameters
315 or in a way that might be widely transferable may be able to utilise a variety of loading
316 schemes [17].

317 We hope that the present piece has catalysed a more open mind-set toward some of
318 the factors that must be considered with regards to interpretation of studies examining HL
319 and LL in resistance training. The discussion of resistance training load is pertinent since
320 most strength coaches first consider maximal strength testing to then make training
321 recommendations based on % 1RM. The purpose of this piece is not necessarily to challenge
322 others’ recommendations regarding this topic; rather, we hope to provide practitioners with

323 the necessary understanding to interpret presently existing research on the topic and
324 recommendations surrounding it that may on the surface seem to be contradictory. The
325 impact of load in resistance training may produce differential adaptations in different aspects
326 of morphology or function. Thus persons should first consider their desired training goals and
327 then decide whether evidence would appear to suggest that the manipulation of load might
328 impact those goals differentially. If the effect of load is presently equivocal for a particular
329 outcome, there are potentially numerous practical implications of being able to self-select an
330 external load. These include: reducing the need for specific facility memberships (e.g. where
331 specifically heavy loads are available), motivating older persons or those who might be less
332 confident using heavy loads, and allowing people to undertake home- or field-based
333 resistance training intervention strategies. Ultimately these might serve to improve exercise
334 adherence. As a final caveat to the content discussed, we recognise that there is very likely a
335 threshold (below which would not produce continued recruitment because of recovery
336 capacity of utilised motor units and muscle fibres, and thus would prevent someone ever
337 reaching true momentary failure) which if not exceeded might produce sub-optimal
338 adaptations, however this has not been identified empirically in any literature and is likely
339 very individual to a person, and possibly exercise based on individual mechanics and muscle
340 fibre type.

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344 **Conflicts of Interest**

345 James Fisher, James Steele and Dave Smith declare that they have no conflicts of interest
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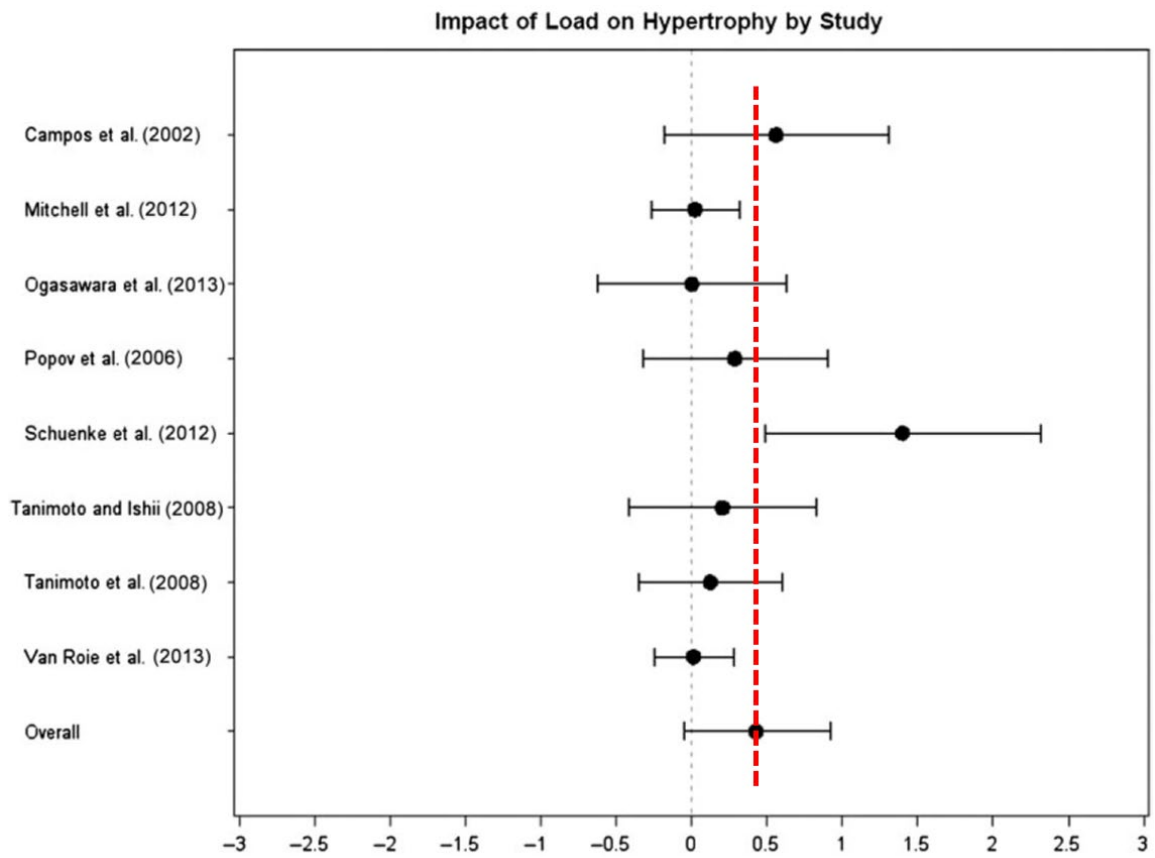
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495

496 Figure 1 Adapted image of Forest plot by Schoenfeld, et al. [6]



497

498 Dotted line represents overall ES. Studies to the right of the dotted line used *in vitro*

499 methods of measuring hypertrophy where studies to the left used *in vivo* methods of

500 measuring hypertrophy.