Longing for a Longitudinal Proxy_ Acutely Measured Surface EMG Amplitude is not a Validated Predictor of Muscle Hypertrophy

Longing for a longitudinal proxy: Acutely measured surface EMG amplitude is not a validated predictor of muscle hypertrophy

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Abstract

Surface electromyography amplitudes are commonly measured in acute sports and exercise science studies to make inferences about muscular strength, performance, and hypertrophic adaptations that may result from different exercises or exercise-related variables. Here, we discuss the presumptive logic and assumptions underlying these inferences, focusing on hypertrophic adaptations for simplicity's sake. In doing so, we present counter-evidence for each of its premises and discuss evidence both for and against the logical conclusion. In view of the limited evidence validating the amplitude of surface electromyograms as a predictor of longitudinal hypertrophic adaptations, coupled with its weak mechanistic foundation, we suggest that acute comparative studies that wish to assess stimulus potency be met with scrutiny.

In view of the growing popularity of surface electromyography (sEMG) studies in sports science, we voiced our concerns in our 2018 review paper on sEMG's use and misuse [1]. Since its publication 3.5 years ago, the paper has garnered well over 150 citations, indicating that it has attracted much attention and the field may indeed be receptive to our concerns. However, over time we learned that many of these citation treated our concerns as minor, inconsequential limitations of sEMG amplitudes rather than serious flaws that undermine their conclusions. In retrospect, this may not be overly surprising as, admittedly, parts of the review were technically dense and required background knowledge of neurophysiology. Given these mis-citations and the continued, pervasive extrapolations of sEMG amplitudes,[1] we wish to clarify and simplify our primary concerns regarding the interpretation of sEMG amplitudes in applied sports science studies, which are complementary to previous critical reviews on sEMG's use and misuse.

To achieve this goal, in this commentary, **we solely focus on one study design which is especially popular and problematic in sports science: using sEMG amplitudes from acute studies to make inferences about**

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[1]By sEMG amplitudes, we refer to statistics summarizing the average degree of variation of the amplitude of the raw sEMG over a given period into a single value, with the most popular estimate being the root mean square amplitude.

longitudinal adaptations, primarily concerning hypertrophy. Studies of this type are ubiquitous and easy to identify. They commonly involve placing surface electrodes on muscles of interest and comparing the sEMG amplitudes that result from two or more exercise variations, loading schemes, or some other exercise-related variable (e.g., exercise order) performed within a single or over a few sessions (i.e., without performing a longitudinal study). For example, researchers may place electrodes on the biceps brachii and have participants perform dumbbell preacher curls and dumbbell incline curls during a single session. Authors then make exercise recommendations based on their findings, indeliberately attributing predictive power to the acutely observed differences in sEMG amplitude; for instance, higher sEMG amplitudes observed during one of the exercises implies that the exercise will elicit greater hypertrophy in the long term. We note that other uses of sEMG, such as to investigate coordination and timing of muscle excitation, are unrelated to our discussion and thus will not be covered, nor will we discuss what information is contained in the sEMG signal. For information regarding the latter, we direct readers to reviews and texts on the topic (see Table 2 in [1]). Instead, our goal with this article is to break down the assertion that sEMG amplitudes can predict hypertrophic adaptations into three premises and a conclusion. Importantly, all three premises that we will cover are necessary for the conclusion that sEMG is a valid predictor of hypertrophy. Yet, only one is dependent on sEMG amplitudes. We argue that all three premises are weak, rendering the conclusion that sEMG amplitudes can be used to predict hypertrophic adaptations tenuous.

Operational Definitions

In this commentary, we simplify our language so as not to overburden the reader with terms with which they may not be familiar. Although some of these terms require knowledge of muscle physiology, a deep understanding of them is not required to grasp the key message of this article.

- Neuromuscular excitation – the electrical signal that causes calcium to be released into the sarcoplasm to enable contraction. This includes the depolarization of the α-motoneuron (neural excitation) and subsequent depolarization of the sarcolemma (muscle excitation). Neural excitation is influenced by motor unit recruitment and rate coding while muscle excitation is affected by changes in the peripheral muscle environment (e.g., $[Ca^{2+}]$ changes).
- Muscle activation – relative binding of calcium to troponin to facilitate cross-bridge attachment.
- Cross-bridge attachment – myosin binding to actin to produce active muscle force.
- Muscle state changes – muscle activation and subsequent cross-bridge attachment.

We lump 'neural excitation' and 'muscle excitation' into 'neuromuscular excitation', which is the electrical phase. Similarly, we sometimes lump 'muscle activation' and 'cross-bridge attachment' into 'muscle state changes', which is the chemomechanical phase. This lumping is justified because the former in each is commonly—though not always—the rate-limiting step [2], and thus, the relationships are close to one-to-one for the purposes of this commentary.

1 The logic of sEMG as a predictor of hypertrophic adaptations

Similar to our 2018 review paper [1], here, we will briefly cover both mechanistic and applied interpretations of sEMG amplitudes. Although seemingly unrelated, these interpretations are closely linked—the latter follows directly from the former. That is, inferences that greater sEMG amplitudes are associated with more favorable hypertrophic adaptations stem from various mechanistic assumptions. The full, often implicit, logical argument is presented below and in Figure 1.

1. sEMG amplitudes are indicative of neuromuscular excitation of the target muscle(s).
2. Neuromuscular excitation is directly related to the state of the muscle.
3. Changes in muscle state drive hypertrophic adaptations.

$\therefore$ Therefore, sEMG is predictive of hypertrophic adaptations.

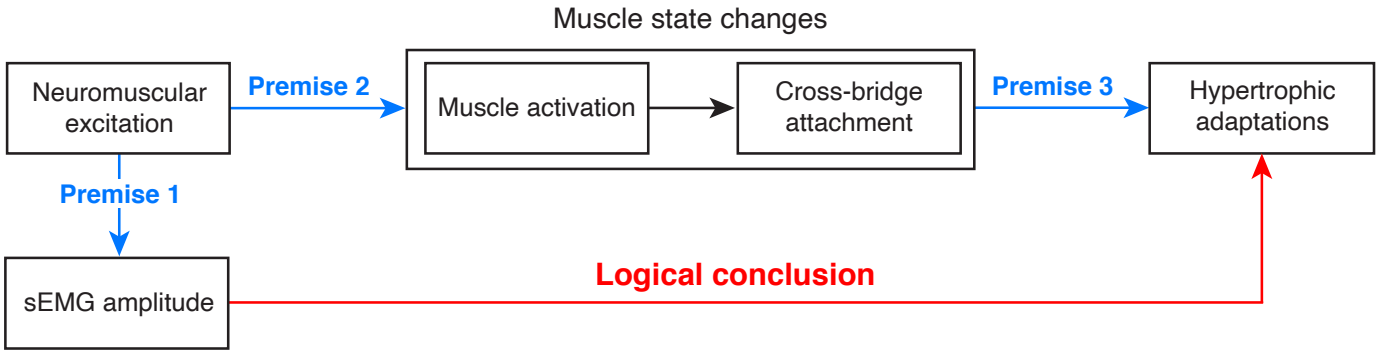

Figure 1: **Mechanistic logic for using surface electromyography (sEMG) as a predictor of hypertrophic adaptations.** sEMG serves as a proxy for neuromuscular excitation. Neuromuscular excitation induces muscle state changes, which are said to drive hypertrophic adaptations. The implication of this logic is that acutely measured differences in sEMG amplitudes can be used to predict hypertrophic adaptations. For this logical conclusion to be true, either (a) all premises must strongly hold; (b) biases or poor relationships in one premise must be "cancelled out" by the other premises; and/or (c) there is some other pathway. *Prima facie*, we consider (b) and (c) to be highly unlikely, so we focus on (a).

1.1 Premise 1: sEMG amplitudes are indicative of neuromuscular excitation of the target muscle(s).

A common assumption among sport and exercise scientists is that sEMG amplitudes are solely a combination of neuromuscular excitation. However, a growing number of human, animal, and modeling studies have shown that sEMG amplitudes and neuromuscular excitation can be uncoupled. For instance, by simply plantar flexing the ankle, Vieira et al. [3] observed a marked decrease in tibialis anterior sEMG amplitude induced by nerve stimulation (M-wave).[2] This indicates that changing a muscle's shape or architecture (i.e., length and pennation angle) will drastically affect the sEMG signal, even when neuromuscular excitation is identical. The biophysical origins of this effect are fairly well understood. In particular, the muscle architecture-dependence of the sEMG signal is a consequence of how the action potentials travel through the muscle relative to the positions of the electrodes [12]. Similarly, electrode configurations, subcutaneous thickness, muscle lengths, and contraction modes will bias the surface electromyogram, resulting in an under- or over-representation of the electrical signal from the target muscle(s) that may vary throughout the range of motion [13–19].

These inconsistencies challenge the premise that sEMG amplitudes collected across different exercises truly reflect differences in neuromuscular excitation. Although normalizing signals to a single maximal value (e.g., maximum voluntary contraction, M-wave) is unlikely to attenuate this effect, the benefits of position-specific normalization remain to be investigated. Indeed, the excitatory origins of sEMG amplitude changes are clearer in well-controlled conditions but can impose an inferential barrier whenever changes in muscle architecture, length, or force are likely to take place [17].

[2] Similar findings have been reported in other studies and muscles [4–11].

1.2 Premise 2: Neuromuscular excitation is directly related to the state of the muscle.

Neuromuscular excitation is the electrical signal that causes calcium to be released into the sarcoplasm to enable contraction. Following this release, the state of the muscle is altered by calcium binding to troponin (activation) to enable cross-bridging (attachment), which together determine the muscle's state [20]. The distinction between neuromuscular excitation and a muscle's state is subtle but meaningful, as the two can be instantaneously decoupled by exploiting their dynamics.[3] This challenges the premise that neuromuscular excitation provides clear insight into a muscle's state. However, Premise 2 can hold in study designs that include non-fatiguing, isotonic, isometric contractions, as one can assume a linear and stable relationship between neuromuscular excitation and a muscle's state.

1.3 Premise 3: Muscle state changes drive hypertrophic adaptations.

The logic that a muscle's state begets its hypertrophy is predicated on the assumptions that (a) changes in muscle state induce muscle protein synthesis (MPS), and (b) MPS triggers a hypertrophic response. It is certainly the case that resistance exercise triggers robust MPS and hypertrophic responses relative to rest [22]. Unfortunately, comparisons to rest tell us little about the muscle state-hypertrophy dose-response relationship.

The relationship between muscle state changes and MPS remains unclear, and the best available evidence suggests it is weak. Morton et al. [23] found that glycogen depletion following exercise, a marker of activation, was only weakly associated with anabolic markers (i.e., mTOR, p70 S6k, etc.; not MPS).[4] Although the investigators did not study MPS directly, the weak relationship observed between muscle state changes and anabolic markers indicates that the muscle state-MPS relationship may indeed be tenuous.

In contrast to the muscle state-MPS relationship, the link between MPS and hypertrophy is mixed and remains to be fully elucidated. Early work suggests little-to-no correlation between MPS and hypertrophy [25], but more recent work that accounts for some methodological shortcomings suggests much stronger correlations ($r > 0.9$) [26]. Although debates are ongoing [22], in some contexts, the jump from MPS to hypertrophy may indeed be a reasonable one.

More broadly, the relationship between muscle state changes and growth—spanning both muscle state to MPS and MPS to growth, which are detailed separately above—is inconsistent across the literature. For example, changes in the muscle state are not necessary for muscle growth, as indicated by studies that have observed growth following stretch protocols in which changes in muscle state did not occur [27]. Evidently, the activation-hypertrophy relationship is not straightforward. The dearth of a clear-cut relationship between muscle state changes and muscle growth undermines Premise 3.

Finally, even if the above premises held, the predictive value of sEMG would still need to be directly validated.

[3] Changing a muscle's state over time (e.g., dynamic contractions or changes in force) will complicate the otherwise straightforward neuromuscular excitation-muscle state relationship [2, 21]. Although this process can be modeled, it is typically not in applied sEMG studies in sports science.

[4] Morton et al. [23] also demonstrate that sEMG amplitudes can be decoupled from (a) muscle state changes, as measured via muscle glycogen depletion, which spans Premises 1 and 2, and (b) anabolic signaling, which spans Premises 1–3. However, the authors employed between- rather than within-subject correlations. Here, we think the more relevant question is the within-subject relationship (see [24]), which may be a fruitful avenue for future research.

1.4 Logical Conclusion: sEMG is predictive of hypertrophic adaptations.

The mechanistic rationale for sEMG being a predictor of hypertrophy is attractive, but as we briefly discussed in the previous sections, there are theoretical concerns that may yield the relationship to be tenuous. In fact, the assertion that sEMG has predictive validity is an example of a slippery slope argument, the strength of which depends on two factors. As eloquently stated by philosopher David Kelley, "The first is the strength of each link in the causal chain; the argument cannot be stronger than its weakest link. The second is the number of links; the more links there are, the more likely it is that other factors could alter the consequences" (p. 123, [28]). Given both the number of links (premises) and their unstable mechanistic foundations, predictive validity arguments for sEMG amplitude are poor. It cannot simply be assumed that a clear relationship between sEMG and longitudinal outcomes exists.

Indirect evidence indicates inconsistent relationships between sEMG amplitudes and growth. On one hand, evidence in favor of the sEMG-hypertrophy relationship is that sEMG amplitudes tend to correspond with growth in the rectus femoris [29–32] and hamstrings [33–36]. For example, multi-joint movements yield low sEMG amplitudes and little growth in the rectus femoris, whereas single-joint movements yield high sEMG amplitudes and marked growth [29–32]. However, one could argue that these results are expected based on biomechanics, meaning there was no clinical equipoise and the sEMG results did not provide novel insight. On the other hand, sEMG amplitudes were not clearly indicative of growth when comparing different contraction modes [15, 37], fatiguing conditions [23, 38–44], and muscle lengths [4, 45–56]. For example, maximum isometric voluntary contractions across a range of knee joint angles produces discordant quadriceps sEMG amplitudes [4, 45–52]. However, greater hypertrophy is commonly observed when the quadriceps are trained isometrically at longer compared to shorter muscle lengths [53–56]. Perhaps the largest discrepancy between sEMG amplitudes and hypertrophy is in the high- versus low-load resistance training literature. When sets are performed to momentary failure, high- and low-loads produce similar growth [38–40] despite high-loads eliciting greater sEMG amplitudes throughout the entire duration of a set [23, 41–44, 57].

As evident from these examples, indirect evidence is mixed regarding the link between sEMG amplitude and hypertrophic responses. Yet, no study has directly investigated and quantified the association between sEMG amplitude and longitudinal outcomes.[5] In quantifying this relationship, several ancillary questions will be answered, including the sensitivity of sEMG as a predictor of hypertrophy. For example, when comparing two exercises, how much greater of a hypertrophic response can we expect from a 10% greater sEMG amplitude? Moderators of this relationship would also be of interest, including the effects of fatigue, contraction mode, and muscle being studied. However, predictive validity does not begin and end with associations.

Establishing predictive validity is a grueling process. To do so, investigators must explicitly demonstrate that any observed relationship is predictive and generalizable to other populations and environments [62]. For sEMG to be validated and accepted as a predictor of longitudinal adaptations, it would need to be *both* associated with *and*

[5] We also acknowledge the T_2-weighted magnetic resonance imaging (MRI) and regional hypertrophy work by Wakahara et al. [58–60] in the triceps brachii and quadriceps and Illera-Dominguez et al. [61] in the hamstrings, quadriceps, and adductors. Although their findings are mixed, there are two caveats to note. Principally, this work used MRI rather than sEMG; to our knowledge, MRI has not been validated against sEMG for intramuscular heterogeneity. Secondly, these studies did not model within-subject relationships directly.

predictive of the outcomes of interest (hypertrophy). Without such work, **it is unacceptable to treat sEMG as a validated predictor of longitudinal adaptations.**

2 Take-Home Points

In light of the aforementioned limitations, the production of acute studies and reviews of comparative studies on acute sEMG amplitudes, with the implicit or explicit purpose of inferring longitudinal adaptations, should be greatly attenuated. The sheer number of these acute comparative sEMG amplitude studies are increasing at what seems to be an exponential rate, without complementary longitudinal studies. This is problematic: If one exercise leads to greater sEMG amplitude than another, the longitudinal implications of such findings are assumed, not evidenced. In the case of hypertrophy, these assumptions are largely unsupported, and similar scrutiny can also be applied to other longitudinal adaptations such as strength. These acute sEMG amplitude studies intended to inform exercise selection without measuring longitudinal adaptations use precious resources, including the time of the researchers, participants, peer-reviewers, editors, and readers, in addition to the costs involved in conducting research.

To be clear,

- At present, acute studies that compare sEMG amplitudes between, for example, two different exercise protocols cannot be used as evidence for longitudinal adaptations (e.g., hypertrophy);
- Acute sEMG amplitude studies *may* be indicative of longitudinal adaptations, but evidence supporting this assertion is lacking. Arguments that contend otherwise are based on tenuous assumptions and are appeals to ignorance;
- Instead of acute comparative sEMG amplitude studies, investigators should focus on longitudinal outcomes of interest (e.g., measures of hypertrophy);
- Despite these limitations, sEMG is a useful tool for specific research questions, such as those related to coordination (e.g., timing of muscle excitation).

3 Conclusion

We contend that continued submissions and publications of acute comparative sEMG amplitude studies with inferences about longitudinal adaptations are flooding the literature. To help remedy this, we propose that journal editors keep the above points in mind before sending these papers out for review, and reviewers who receive such papers should be mindful of the limitations we mentioned. Unless authors communicate the value of their study independently of longitudinal outcomes and beyond that which would be expected from basic biomechanics or functional anatomy, their findings and implications should be appraised critically.

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References

[1] Andrew D Vigotsky, Israel Halperin, Gregory J Lehman, Gabriel S Trajano, and Taian M Vieira. Interpreting signal amplitudes in surface electromyography studies in sport and rehabilitation sciences. *Frontiers in Physiology*, 8:985, 2018.

[2] Felix E Zajac. Muscle and tendon: properties, models, scaling, and application to biomechanics and motor control. *Critical reviews in biomedical engineering*, 17(4):359–411, 1989.

[3] Taian M Vieira, Maria Cristina Bisi, Rita Stagni, and Alberto Botter. Changes in tibialis anterior architecture affect the amplitude of surface electromyograms. *Journal of NeuroEngineering and Rehabilitation*, 14(1):81, 2017.

[4] Marcel B. Lanza, Thomas G. Balshaw, and Jonathan P. Folland. Do changes in neuromuscular activation contribute to the knee extensor angle–torque relationship? *Experimental Physiology*, 102(8):962–973, Aug 2017.

[5] E. Marsh, D. Sale, A. J. McComas, and J. Quinlan. Influence of joint position on ankle dorsiflexion in humans. *Journal of Applied Physiology: Respiratory, Environmental and Exercise Physiology*, 51(1):160–167, Jul 1981.

[6] Alain Frigon, Timothy J. Carroll, Kelvin E. Jones, E. Paul Zehr, and David F. Collins. Ankle position and voluntary contraction alter maximal M waves in soleus and tibialis anterior. *Muscle & Nerve*, 35(6):756–766, Jun 2007.

[7] Brandon W. Collins and Duane C. Button. The effect of shoulder position on motor evoked and maximal muscle compound action potentials of the biceps brachii. *Neuroscience Letters*, 665:206–211, Feb 2018.

[8] Brandon Wayne Collins, Edward W. J. Cadigan, Lucas Stefanelli, and Duane C. Button. Corticospinal excitability of the biceps brachii is shoulder position dependent. *Journal of Neurophysiology*, 118(6):3242–3251, Dec 2017.

[9] Jeremy P. M. Mogk, Lynn M. Rogers, Wendy M. Murray, Eric J. Perreault, and James W. Stinear. Corticomotor excitability of arm muscles modulates according to static position and orientation of the upper limb. *Clinical Neurophysiology : Official Journal of the International Federation of Clinical Neurophysiology*, 125(10):2046–2054, Oct 2014.

[10] Siobhan C. Dongés, Janet L. Taylor, and James L. Nuzzo. Elbow angle modulates corticospinal excitability to the resting biceps brachii at both spinal and supraspinal levels. *Experimental Physiology*, 104(4):546–555, Apr 2019.

[11] James L. Nuzzo, Gabriel S. Trajano, Benjamin K. Barry, Simon C. Gandevia, and Janet L. Taylor. Arm posture-dependent changes in corticospinal excitability are largely spinal in origin. *Journal of Neurophysiology*, 115(4):2076–2082, Apr 2016.

[12] Luca Mesin, Roberto Merletti, and Taian MM Vieira. Insights gained into the interpretation of surface electromyograms from the gastrocnemius muscles: a simulation study. *Journal of biomechanics*, 44(6):1096–1103, 2011.

[13] Felipe D Mancebo, Hélio V Cabral, Leonardo ML de Souza, Liliam F de Oliveira, and Taian M Vieira. Innervation zone locations distribute medially within the pectoralis major muscle during bench press exercise. *Journal of Electromyography and Kinesiology*, 46:8–13, 2019.

[14] Taian Martins Vieira. Interpretation of surface electromyograms: The spatial localisation of muscle activity. In *International Conference on NeuroRehabilitation*, pages 1148–1151. Springer, 2018.

[15] JR Potvin. Effects of muscle kinematics on surface emg amplitude and frequency during fatiguing dynamic contractions. *Journal of Applied Physiology*, 82(1):144–151, 1997.

[16] Verne T Inman, HJ Ralston, JB de CM Saunders, MB Bertram Feinstein, and Elwood W Wright Jr. Relation of human electromyogram to muscular tension. *Electroencephalography and clinical neurophysiology*, 4(2):187–194, 1952.

[17] Dario Farina. Interpretation of the surface electromyogram in dynamic contractions. *Exercise and sport sciences reviews*, 34(3):121–127, 2006.

[18] K. G. Keenan, D. Farina, K. S. Maluf, R. Merletti, and R. M. Enoka. Influence of amplitude cancellation on the simulated surface electromyogram. *J Appl Physiol (1985)*, 98(1):120–131, Jan 2005.

[19] A. Rainoldi, M. Nazzaro, R. Merletti, D. Farina, I. Caruso, and S. Gaudenti. Geometrical factors in surface EMG of the vastus medialis and lateralis muscles. *J Electromyogr Kinesiol*, 10(5):327–336, Oct 2000.

[20] Jack M Winters. Hill-based muscle models: a systems engineering perspective. In *Multiple muscle systems*, pages 69–93. Springer, 1990.

[21] George I. Zahalak and Shi-Ping Ma. Muscle Activation and Contraction: Constitutive Relations Based Directly on Cross-Bridge Kinetics. *Journal of Biomechanical Engineering*, 112(1):52–62, Feb 1990.

[22] Vandré Casagrande Figueiredo. Revisiting the roles of protein synthesis during skeletal muscle hypertrophy induced by exercise. *American Journal of Physiology. Regulatory, Integrative and Comparative Physiology*, 317(5):709–718, Nov 2019.

[23] Robert W Morton, Michael W Sonne, Amanda Farias Zuniga, Ibrahim YZ Mohammad, Amanda Jones, Chris McGlory, Peter J Keir, Jim R Potvin, and Stuart M Phillips. Muscle fibre activation is unaffected by load and repetition duration when resistance exercise is performed to task failure. *The Journal of physiology*, 597(17):4601–4613, 2019.

[24] Andrew D. Vigotsky, Brad J. Schoenfeld, Christian Than, and J. Mark Brown. Methods matter: the relationship between strength and hypertrophy depends on methods of measurement and analysis. *PeerJ*, 6:e5071., Jun 2018.

[25] Cameron J Mitchell, Tyler A Churchward-Venne, Gianni Parise, Leeann Bellamy, Steven K Baker, Kenneth Smith, Philip J Atherton, and Stuart M Phillips. Acute post-exercise myofibrillar protein synthesis is not correlated with resistance training-induced muscle hypertrophy in young men. *PloS one*, 9(2):e89431, 2014.

[26] Felipe Damas, Stuart M Phillips, Cleiton A Libardi, Felipe C Vechin, Manoel E Lixandrão, Paulo R Jannig, Luiz AR Costa, Aline V Bacurau, Tim Snijders, Gianni Parise, et al. Resistance training-induced changes in integrated myofibrillar protein synthesis are related to hypertrophy only after attenuation of muscle damage. *The Journal of physiology*, 594(18):5209–5222, 2016.

[27] Alfred L Goldberg, Joseph D Etlinger, David F Goldspink, and Charles Jablecki. Mechanism of work-induced hypertrophy of skeletal muscle. *Medicine and science in sports*, 7(3):185–198, 1975.

[28] David Kelley. *The art of reasoning: An introduction to logic and critical thinking*. WW Norton & Company, 2013.

[29] Ryoichi Ema, Taku Wakahara, Naokazu Miyamoto, Hiroaki Kanehisa, and Yasuo Kawakami. Inhomogeneous architectural changes of the quadriceps femoris induced by resistance training. *European journal of applied physiology*, 113(11):2691–2703, 2013.

[30] Ryoichi Ema, Masanori Sakaguchi, Ryota Akagi, and Yasuo Kawakami. Unique activation of the quadriceps femoris during single-and multi-joint exercises. *European journal of applied physiology*, 116(5):1031–1041, 2016.

[31] N Yamashita. Emg activities in mono-and bi-articular thigh muscles in combined hip and knee extension. *European journal of applied physiology and occupational physiology*, 58(3):274–277, 1988.

[32] Makoto Fujiwara and John V Basmajian. Electromyographic study of two-joint muscles. *American Journal of Physical Medicine & Rehabilitation*, 54(5):234–242, 1975.

[33] William P Ebben, David H Leigh, and Randall L Jensen. The role of the back squat as a hamstring training stimulus. *Strength & Conditioning Journal*, 22(5):15, 2000.

[34] K1 Bloomquist, Henning Langberg, Stine Karlsen, S Madsgaard, M Boesen, and Truls Raastad. Effect of range of motion in heavy load squatting on muscle and tendon adaptations. *European journal of applied physiology*, 113(8):2133–2142, 2013.

[35] Matthew N Bourne, Morgan D Williams, David A Opar, Aiman Al Najjar, Graham K Kerr, and Anthony J Shield. Impact of exercise selection on hamstring muscle activation. *British journal of sports medicine*, 51(13):1021–1028, 2017.

[36] Matthew N Bourne, Steven J Duhig, Ryan G Timmins, Morgan D Williams, David A Opar, Aiman Al Najjar, Graham K Kerr, and Anthony J Shield. Impact of the nordic hamstring and hip extension exercises on hamstring architecture and morphology: implications for injury prevention. *British Journal of Sports Medicine*, 51(5):469–477, 2017.

[37] Brad J Schoenfeld, Dan I Ogborn, Andrew D Vigotsky, Martino V Franchi, and James W Krieger. Hypertrophic effects of concentric vs. eccentric muscle actions: a systematic review and meta-analysis. *The Journal of Strength & Conditioning Research*, 31(9):2599–2608, 2017.

[38] Cameron J. Mitchell, Tyler A. Churchward-Venne, Daniel W. D. West, Nicholas A. Burd, Leigh Breen, Steven K. Baker, and Stuart M. Phillips. Resistance exercise load does not determine training-mediated hypertrophic gains in young men. *Journal of Applied Physiology*, 113(1):71, Jul 2012.

[39] Robert W Morton, Sara Y Oikawa, Christopher G Wavell, Nicole Mazara, Chris McGlory, Joe Quadrilatero, Brittany L Baechler, Steven K Baker, and Stuart M Phillips. Neither load nor systemic hormones determine resistance training-mediated hypertrophy or strength gains in resistance-trained young men. *Journal of applied physiology*, 121(1):129–138, 2016.

[40] Brad J. Schoenfeld, Jozo Grgic, Dan Ogborn, and James W. Krieger. Strength and Hypertrophy Adaptations Between Low- vs. High-Load Resistance Training: A Systematic Review and Meta-analysis. *Journal of Strength and Conditioning Research*, 31(12):3508–3523, Dec 2017.

[41] Nathaniel D. M. Jenkins, Terry J. Housh, Haley C. Bergstrom, Kristen C. Cochrane, Ethan C. Hill, Cory M. Smith, Glen O. Johnson, Richard J. Schmidt, and Joel T. Cramer. Muscle activation during three sets to failure at 80 vs. 30 % 1RM resistance exercise. *European Journal of Applied Physiology*, 115(11):2335–2347, Nov 2015.

[42] David P Looney, William J Kraemer, Michael F Joseph, Brett A Comstock, Craig R Denegar, Shawn D Flanagan, Robert U Newton, Tunde K Szivak, William H DuPont, David R Hooper, et al. Electromyographical and perceptual responses to different resistance intensities in a squat protocol: does performing sets to failure with light loads produce the same activity? *The Journal of Strength & Conditioning Research*, 30(3):792–799, 2016.

[43] Brad J Schoenfeld, Bret Contreras, Jeffrey M Willardson, Fabio Fontana, and Gul Tiryaki-Sonmez. Muscle activation during low-versus high-load resistance training in well-trained men. *European journal of applied physiology*, 114(12):2491–2497, 2014.

[44] Brad J Schoenfeld, Bret Contreras, Andrew D Vigotsky, Dan Ogborn, Fabio Fontana, and Gul Tiryaki-Sonmez. Upper body muscle activation during low-versus high-load resistance exercise in the bench press. *Isokinetics and Exercise Science*, 24(3):217–224, 2016.

[45] Roland Becker and Friedemann Awiszus. Physiological alterations of maximal voluntary quadriceps activation by changes of knee joint angle. *Muscle & Nerve*, 24(5):667–672, May 2001.

[46] Keitaro Kubo, Naoya Tsunoda, Hiroaki Kanehisa, and Tetsuo Fukunaga. Activation of agonist and antagonist muscles at different joint angles during maximal isometric efforts. *European Journal of Applied Physiology*, 91(2):349–352, Mar 2004.

[47] Danny M. Pincivero, Yuliya Salfetnikov, Robert M. Campy, and Alan J. Coelho. Angle- and gender-specific quadriceps femoris muscle recruitment and knee extensor torque. *Journal of Biomechanics*, 37(11):1689–1697, Nov 2004.

[48] E. M. Hasler, J. Denoth, A. Stacoff, and W. Herzog. Influence of hip and knee joint angles on excitation of knee extensor muscles. *Electromyography and Clinical Neurophysiology*, 34(6):355–361, Sep 1994.

[49] Nicolas Babault, Michel Pousson, Anne Michaut, and Jacques Van Hoecke. Effect of quadriceps femoris muscle length on neural activation during isometric and concentric contractions. *Journal of Applied Physiology*, Mar 2003.

[50] Roger M. Zabik and Mary L. Dawson. Comparison of Force and Peak EMG during a Maximal Voluntary Isometric Contraction at Selected Angles in the Range of Motion for Knee Extension. *Perceptual and Motor Skills*, 83(3):976–978, Dec 1996.

[51] S. A. Newman, G. Jones, and D. J. Newham. Quadriceps voluntary activation at different joint angles measured by two stimulation techniques. *European Journal of Applied Physiology*, 89(5):496–499, Jun 2003.

[52] R. D. Kooistra, C. J. de Ruiter, and A. de Haan. Conventionally assessed voluntary activation does not represent relative voluntary torque production. *European Journal of Applied Physiology*, 100(3):309–320, Jun 2007.

[53] Dustin J. Oranchuk, Adam G. Storey, André R. Nelson, and John B. Cronin. Isometric training and long-term adaptations: Effects of muscle length, intensity, and intent: A systematic review. *Scandinavian Journal of Medicine & Science in Sports*, 29(4):484–503, Apr 2019.

[54] Marika Noorkõiv, Kazunori Nosaka, and Anthony J. Blazevich. Neuromuscular adaptations associated with knee joint angle-specific force change. *Medicine and Science in Sports and Exercise*, 46(8):1525–1537, Aug 2014.

[55] K. Kubo, K. Ohgo, R. Takeishi, K. Yoshinaga, N. Tsunoda, H. Kanehisa, and T. Fukunaga. Effects of isometric training at different knee angles on the muscle-tendon complex in vivo. *Scandinavian Journal of Medicine & Science in Sports*, 16(3):159–167, Jun 2006.

[56] Luis M. Alegre, Asunción Ferri-Morales, Raúl Rodriguez-Casares, and Xavier Aguado. Effects of isometric training on the knee extensor moment-angle relationship and vastus lateralis muscle architecture. *European Journal of Applied Physiology*, 114(11):2437–2446, Nov 2014.

[57] Brenda Bigland-Ritchie. Emg/force relations and fatigue of human voluntary contractions. *Exercise and sport sciences reviews*, 9(1):75–118, 1981.

[58] Taku Wakahara, Naokazu Miyamoto, Norihide Sugisaki, Koichiro Murata, Hiroaki Kanehisa, Yasuo Kawakami, Tetsuo Fukunaga, and Toshimasa Yanai. Association between regional differences in muscle activation in one session of resistance exercise and in muscle hypertrophy after resistance training. *European journal of applied physiology*, 112(4):1569–1576, 2012.

[59] Taku Wakahara, Atsuki Fukutani, Yasuo Kawakami, and Toshimasa Yanai. Nonuniform muscle hypertrophy: its relation to muscle activation in training session. *Medicine and science in sports and exercise*, 45(11):2158–2165, 2013.

[60] Taku Wakahara, Ryoichi Ema, Naokazu Miyamoto, and Yasuo Kawakami. Inter-and intramuscular differences in training-induced hypertrophy of the quadriceps femoris: association with muscle activation during the first training session. *Clinical Physiology and Functional Imaging*, 37(4):405–412, 2017.

[61] Víctor Illera-Domínguez, Sergi Nuell, Gerard Carmona, Josep M. Padullés, Xavier Padullés, Mario Lloret, Roser Cussó, Xavier Alomar, and Joan A. Cadefau. Early Functional and Morphological Muscle Adaptations During Short-Term Inertial-Squat Training. *Frontiers in Physiology*, 9, 2018.

[62] Ewout W Steyerberg et al. *Clinical prediction models*. Springer, 2019.