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How much stronger are muscles eccentrically than concentrically? Meta-analysis of the influences of sex, age, joint action, and velocity

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*For correspondence: j.nuzzo@ecu.edu.au
Twitter: @JamesLNuzzo

James L. Nuzzo,[1] Matheus D. Pinto,[1] Kazunori Nosaka,[1] James Steele,[2]

[1] Centre for Human Performance, School of Medical and Health Sciences, Edith Cowan University, Joondalup, Australia
[2] Faculty of Sport, Health, and Social Sciences, Solent University, Southampton, United Kingdom

ABSTRACT

For decades, researchers have observed that eccentric (ECC) muscle strength is greater than concentric (CON) strength. However, knowledge of the ECC:CON strength ratio is incomplete and might inform ECC exercise prescriptions. Our purposes were to determine the magnitude of the ECC:CON ratio and explore if sex, age, joint actions/exercises, and movement velocity impact it. A total of 1,393 ECC:CON ratios, aggregated from 11,477 individuals who made up 502 groups in 290 studies, were examined. Approximately 98% of measurements occurred on isokinetic machines. Bayesian meta-analyses were performed using log-ratios as response variables then exponentiated back to raw ratios. The overall main model estimate for the ECC:CON ratio was 1.41 [95% credible interval (CI): 1.38–1.44]. The ECC:CON ratio was slightly less in men (1.39 [CI: 1.35–1.42]) than women (1.46 [CI: 1.42–1.51]), but greater in older (1.65 [CI: 1.59–1.72]) than younger adults (1.38 [CI: 1.36–1.41]). The ratio was similar between grouped upper-body (1.43 [CI: 1.40–1.47]) and lower-body joint actions/exercises (1.40 [CI: 1.37–1.43]). However, heterogeneity in the ratio existed across joint actions/exercises, with point estimates ranging from 1.32 to 2.75. The ECC:CON ratio was mostly greatly impacted by movement velocity, with a 0.21% increase in the ratio for every 1°/s increase in velocity. The results show ECC strength is ~40% greater than CON strength. However, the ECC:CON ratio is greatly affected by movement velocity and to a lesser extent by age. Differences between joint actions/exercises likely exist but more data are needed to provide more precise estimates.

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1.0 Introduction

A repetition of a resistance exercise usually involves both an active muscle shortening phase (concentric; CON) and active muscle lengthening phase (eccentric; ECC). For several decades, researchers have reported that volitional muscle forces are greater during the ECC than CON phase of exercise repetitions [1-3]. However, the magnitude of this difference, which is often reported as the ECC:CON strength ratio, is not entirely clear, and it might be impacted by factors such as sex [4-7], age [7], injury [8, 9], muscle group [5, 6], and movement velocity [4, 5]. In one study, Colliander and Tesch [4] submitted 27 healthy men and 13 healthy women to maximal strength testing on an isokinetic dynamometer and found that the ECC:CON strength ratio was greater in women than men (1.74 vs 1.40), the quadriceps than hamstrings (1.35 vs 1.10), and at faster than slower movement velocity (2.01 vs 1.35). Hollander et al. [6] reported somewhat similar results when measuring ECC:CON strength ratios with the one repetition maximum (1RM). In their study, the ECC:CON strength ratio for the leg curl was 1.83 for women and 1.30 in men [6]. Moreover, across the six exercises they assessed, the ECC:CON strength ratio ranged from 1.57 to 2.87 in women and 1.30 to 1.51 in men [6].

Though differences between ECC and CON muscle strength have been observed in human appendicular muscles since at least the 1960s [1-3], a review of the ECC:CON strength ratio, and the factors that impact it, appears lacking. Knowledge of this ratio might have implications for the way resistance exercise is prescribed. In recent years, researchers and practitioners have expressed great interest in accentuated ECC and ECC-only resistance exercise. A number of reviews on ECC resistance exercise have been published in sports science journals [10-18], and 75-95% of strength and conditioning coaches now say they prescribe ECC resistance exercise [19-21]. Moreover, new resistance exercise technologies, such as connected adaptive resistance exercise (CARE) machines [22], have potential to deliver accentuated ECC loads in a more feasible way than free weights, plate-loaded machines, and weight stack machines – the equipment most commonly used by coaches to deliver ECC overload [20, 23, 24]. Nevertheless, there is no consensus on the magnitude of ECC overload that should be prescribed and whether factors such as the exercise performed should impact the magnitude of overload.

Practitioners and researchers appear to prescribe a wide range of relative loads for accentuated ECC and ECC-only resistance exercise. According to one survey, coaches prescribe ECC overload ranging from 100 to 150% of the CON 1RM [20]. According to our brief review (Table 1), researchers prescribe ECC loads that range from 105% to 190% of the CON 1RM or CON training load. Thus, knowledge of the magnitude of the ECC:CON strength ratio, and the factors that impact it, could help to inform and optimize delivery of ECC overload for specific exercises and populations, particularly as exercise technology continues to evolve to make accentuated ECC exercise safer and more feasible. Therefore, the purpose of this review was to determine how much stronger muscles are during ECC than CON muscle actions. Specifically, we examined the extent to which sex, age, joint actions/exercises, and movement velocity impact the ECC:CON strength ratio. These moderators were tested to provide more specific guidance to exercise practitioners on factors that warrant consideration for ECC overload prescriptions.

Table 1. Magnitude of eccentric (ECC) overload in acute exercise studies and longer-term training studies.

Study	Sex	Age (y)	Exercise	ECC overload
Acute exercise studies				
Doan et al. [46]	M	< 60	Bench press	1.05 CON 1RM
Ojasta and Hakkinen [47]	M	< 60	Bench press	1.05–1.2x CON 1RM
Sheppard et al. [48]	M	< 60	Bench press	1.2x CON 1RM
Montalvo et al. [49]	M	< 60	Bench press	1.05x–1.2x CON 1RM
Sarto et al. [50]	M	< 60	Leg press	1.5x CON 1RM
Wagle et al. [51]	M	< 60	Squat	1.05x CON 1RM
Wagle et al. [52]	M	< 60	Squat	1.05x CON 1RM
Training studies				
Coratella et al. [53]	M	< 60	Knee extension	1.2x CON 1RM
Godard et al. [54]	MF	< 60	Knee extension	1.4x CON training load
Walker et al. [55]	M	< 60	Knee extension	1.4x CON training load
Hortobágyi et al. [56]	F	≥ 60	Knee extension	1.5x CON training load
Friedmann-Bette et al. [57]	M	< 60	Knee extension	1.9x CON training load
Brandenburg and Docherty [58]	M	< 60	Elbow flexion, extension	1.1x–1.2x CON 1RM
English et al. [59]	M	< 60	Leg press, calf raise	1.38x CON 1RM
Tøien et al. [60]	M	< 60	Leg press	1.5x CON 1RM
Franchi et al. [61]	M	< 60	Leg press	80% of ECC 1RM
Seliger et al. [62]	M	< 60	Squat	1.4x–1.5x CON 1RM
Schroeder et al. [63]	F	< 60	Various upper- and lower-body exercises	1.25x CON 1RM

2.0 Methods

2.1 Literature search

To determine the extent to which ECC and CON muscle strength differ, we first searched for relevant literature. The search was thorough, but not necessarily systematic or exhaustive, and instead was a 'snowballing' approach [25]. Relevant keyword searches were performed in PubMed and Google Scholar (e.g., "isokinetic" AND "eccentric" AND "concentric"; "eccentric 1RM"; "isokinetic force-velocity"). The authors' digital files were also searched, and reference lists of eligible articles were screened to identify additional papers. The searches were performed between May and July 2022 but were otherwise not limited by publication date.

2.2 Eligibility

A paper was eligible for inclusion into the review if the following conditions were met: (a) data were collected in human subjects; (b) data were acquired during volitional strength tests; (c) subjects were apparently healthy; (d) the mean age of subjects was ≥18 years; (d) means of ECC and CON strength, or the ECC:CON ratio, were reported; and (e) strength data were reported in absolute units rather than body mass-normalized units. Both cross-sectional and exercise training studies were eligible for inclusion into the review.

2.3 Data extraction

The data extracted from papers included sample size, number of study groups, study type (non-training or training study), sex, age group, joint actions/exercises, movement velocity, and means and standard deviations (SD) of the ECC:CON strength ratios or the ECC and CON strength values. For age categorization, if the mean age of a study group was 18-59 years then the group was classified as "younger adults." If the mean age was ≥60 years then the group was classified as "older adults." Younger adult groups were sometimes comprised of competitive athletes.

In instances of unilateral strength assessments where data were available from both the right and left limbs, the data extracted from the paper were from the right limb. In instances of unilateral assessments where data were available from both the dominant and non-dominant limbs, the data extracted were from the dominant limb. For isokinetic strength tests, peak torques were always extracted instead of average torques. However, if a study reported only average torques, then average torques were extracted. With training studies, baseline strength scores were extracted for each group. Finally, for papers, in which data were presented in figures, muscle strength values were estimated using a graph digitzer (WebPlotDigitizer, https://automeris.io).

2.4 Statistical analyses

All analysis code utilized is presented in the supplementary materials (https://osf.io/8vt9h/). Given the aim of this research, we opted to take an estimation-based approach [26], based within a Bayesian framework [27]. For all analyses, effect estimates and their precision, along with conclusions based upon them, were interpreted continuously and probabilistically, considering data quality, plausibility of effect, and previous literature, all within the context of each outcome [28]. The main exploratory meta-analysis was performed using the 'brms' package [29] with posterior draws for visualization taken using 'tidybayes' [30] and 'emmeans' [31], and effect sizes calculated using the 'metafor' package [32] in R (v 4.1.2; R Core Team, https://www.r-project.org/) and RStudio (v 2022.02.03+492, RStudio Team, https://www.rstudio.com/). All data visualizations were made using 'ggplot2' [33] and 'patchwork' [34]. Tables were produced using 'formattable' [35].

We were interested in estimating the ECC:CON strength ratio, thus the log ratio was used as our effect size measure for modelling purposes. Where both mean and variance information were available for both ECC and CON strength in the original study, we calculated this for correlated study designs as per Lajeunesse [36]. When only the mean of the ratio and its variance were reported in the original study, we used the log transformed mean [37].

As the included studies often had multiple groups/conditions, and reported multiple strength measures within these, the data had a nested structure. Therefore, multilevel mixed-effects meta-analyses were performed with both inter-study and intra-study groups included as nested random intercepts in the model. Effects were weighted by inverse sampling variance to account for the within- and between-study variance. A main model included all ratios reported for all groups in each study. We conducted meta-regression and sub-group analyses of moderators (i.e., predictors of effects). Moderators examined included subject sex (male vs females), age (younger adults vs older adults), upper- vs lower-body joint actions/exercises, and velocity of movement[1]. The upper-body group consisted of the shoulder, elbow, and wrist. The lower-body group consisted of the hip, knee, and ankle, with the trunk excluded. Additional exploratory models of specific joint actions/exercises[2] were also performed.

For all models, we used uninformed priors (due to the number of effects we anticipated that the likelihood would overwhelm posterior estimates) and 23[3] Monte Carlo Markov Chains with 2000 warmup and 6000 sampling iterations. All models had $\hat{R}$ value of 1.00 and trace plots were produced to visually examine chain convergence along with posterior predictive checks, which are included in the supplementary materials (https://osf.io/8vt9h/; see folder "Trace plots and posterior predictive checks"). Draws were taken from the posterior distributions to calculate the mean and 95% quantile interval (referred to as the 'credible' interval; CI) for each parameter estimate. These gave us the most probable value of the parameter, in addition to the range from the 2.5% to the 97.5% percentiles. We also constructed 95% prediction intervals for the main model. Log ratios were transformed back to the raw ratio scale for reporting in all instances.

3.0 Results

A total of 290 studies were identified (see https://osf.io/b84ng/ for list of studies). Nevertheless, not all reported data were included in the meta-analyses. As such, the summary table of model estimates notes the number of effects, studies, and groups within studies for each estimate (Table 2). The earliest study was published in 1965 and the latest in 2022. The studies included 11,477 participants from 502 separate study groups with a median sample size of 15 (range = 2 to 734). Some studies did not report sex or age. However, 15% of studies included both male and female subjects, 59% included only males, and 23% included only females. A total of 89% included only younger adults, 9% included only older adults, and 0.3% included

[1] Note, for velocity of movement we limited this to studies reporting this in degrees (°) / s as this constituted the majority of observed effects.
[2] Note, this exploratory model included velocity and age (grand mean centred) as a fixed effect to adjust for the fact that some joints only had low numbers of effects at specific velocities or were from studies in one age group, and we anticipated that both velocity and age would impact the ECC:CON ratio. Also, bench press, military press, and lat pulldown were excluded as only one study had measured these exercises.
[3] *C* -1 where *C* was the number of cores available on the computer used to run the analysis (build available here: https://uk.pcpartpicker.com/list/C6VXRT).

both younger and older adults. The proportion of studies that involved exercise training interventions was 18.7%. The vast majority of studies (98%) measured ECC and CON strength using isokinetic dynamometry. The velocities used in these isokinetic assessments ranged from 2°/s to 360°/s.

Table 2. Summary of eccentric:concentric (ECC:CON) strength ratios from all meta-analysis models.

Model	Estimate	Lower CI	Upper CI	No. Effects	No. Studies	No. Groups
Overall Pooled	1.40	1.38	1.43	1276	270	469
Sex				1036	197	366
Female	1.46	1.42	1.51			
Male	1.39	1.35	1.42			
Age (y)				1260	267	464
< 60	1.38	1.36	1.41			
≥ 60	1.65	1.59	1.72			
Joint action / exercise				1241	259	452
Lower-body	1.40	1.37	1.43			
Upper-body	1.43	1.40	1.47			
Velocity (°/s)				1213	244	434
30	1.26	1.23	1.29			
60	1.34	1.31	1.37			
90	1.43	1.40	1.46			
120	1.53	1.49	1.56			
150	1.62	1.59	1.66			
180	1.73	1.69	1.77			
210	1.85	1.81	1.89			
240	1.97	1.92	2.01			
270	2.10	2.05	2.15			
300	2.24	2.19	2.29			
330	2.39	2.33	2.44			
360	2.55	2.48	2.61			

CI = Credible Interval

3.1 Main model

The overall estimate from the main model revealed an ECC:CON ratio of 1.40 with CIs suggesting that the parameter value lay between 1.38 to 1.43 with 95% probability. Prediction intervals were wide suggesting between-effect heterogeneity, with most of this variance being accounted for at the study level (see https://osf.io/ag83u).

1 displays the model mean and interval estimates for each study in addition to the overall estimates and prediction interval.

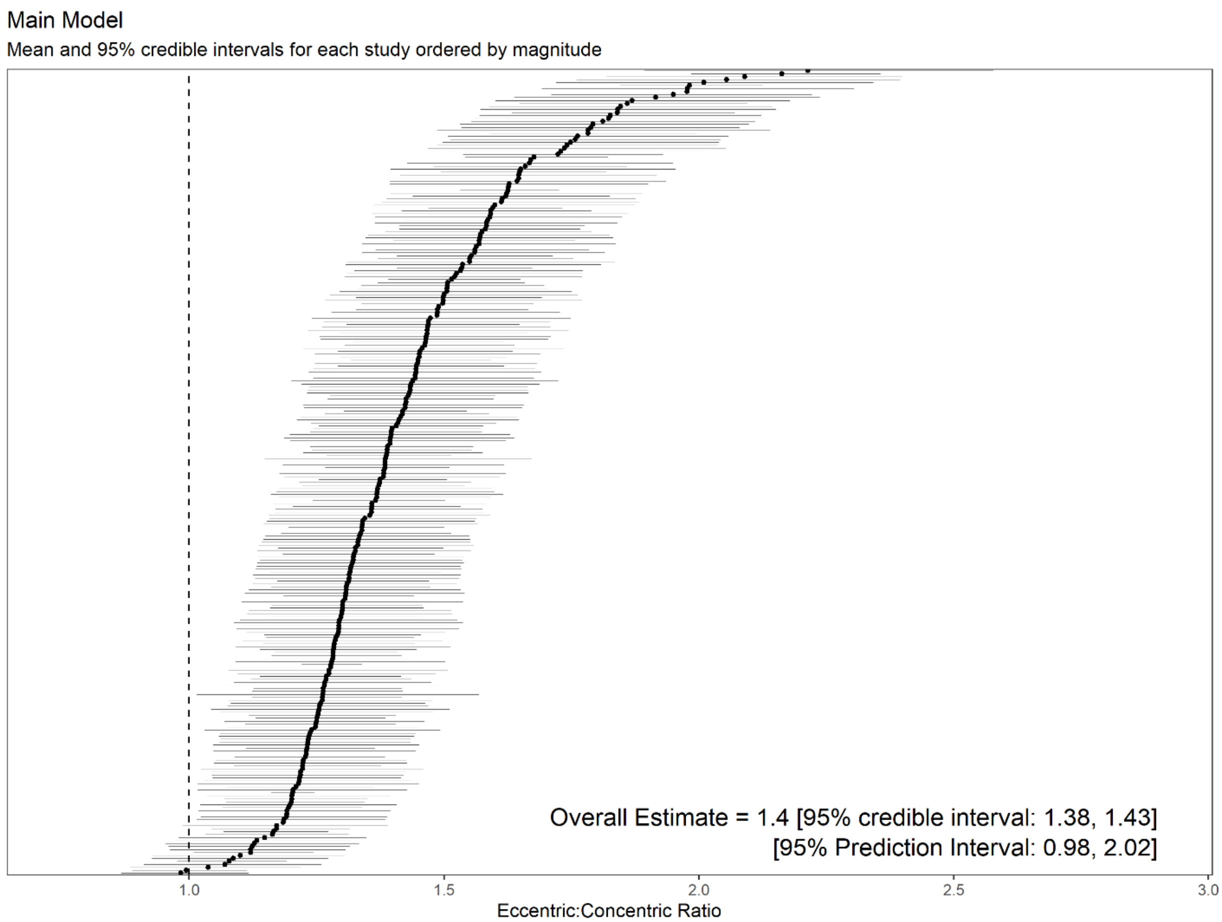

Figure 1. Means and 95% credible intervals of all eccentric:concentric (ECC:CON) strength ratios included in the meta-analysis (*n* = 1,393).

3.2 Moderators

Estimates of ECC:CON strength ratios by sex, age group, upper- vs lower-body joint actions/exercises, and velocity are presented in Table 2. The ECC:CON ratio was lower in men compared to women, but only slightly (men = 1.39 [95% CI: 1.35 to 1.42]; women = 1.46 [95% CI: 1.42 to 1.51]). However, the ratio was greater in older adults (1.65 [95% CI: 1.59 to 1.72]) compared to younger adults (1.38 [95% CI: 1.36 to 1.41]). Whilst in general there was little difference in the ECC:CON strength ratio between upper-body (1.43 [95% CI: 1.40 to 1.47]) and lower-body joint actions/exercises (1.40 [95% CI: 1.37 to 1.43]), there did appear to be some heterogeneity between joint actions/exercises effects on ECC:CON from our exploratory model[4] (Figure 2). However, estimates were imprecise for some joint actions/exercises (e.g., squat, trunk lateral flexion, hip internal and external rotators, and both wrist flexors and extensors). There was a clear log-linear relationship with velocity of movement where ECC:CON increased by 0.21% for every 1°/s increase in velocity (Figure 3).

[4] The number of effects in the exploratory joint action/exercise model was 1182 across 423 groups from 246 studies.

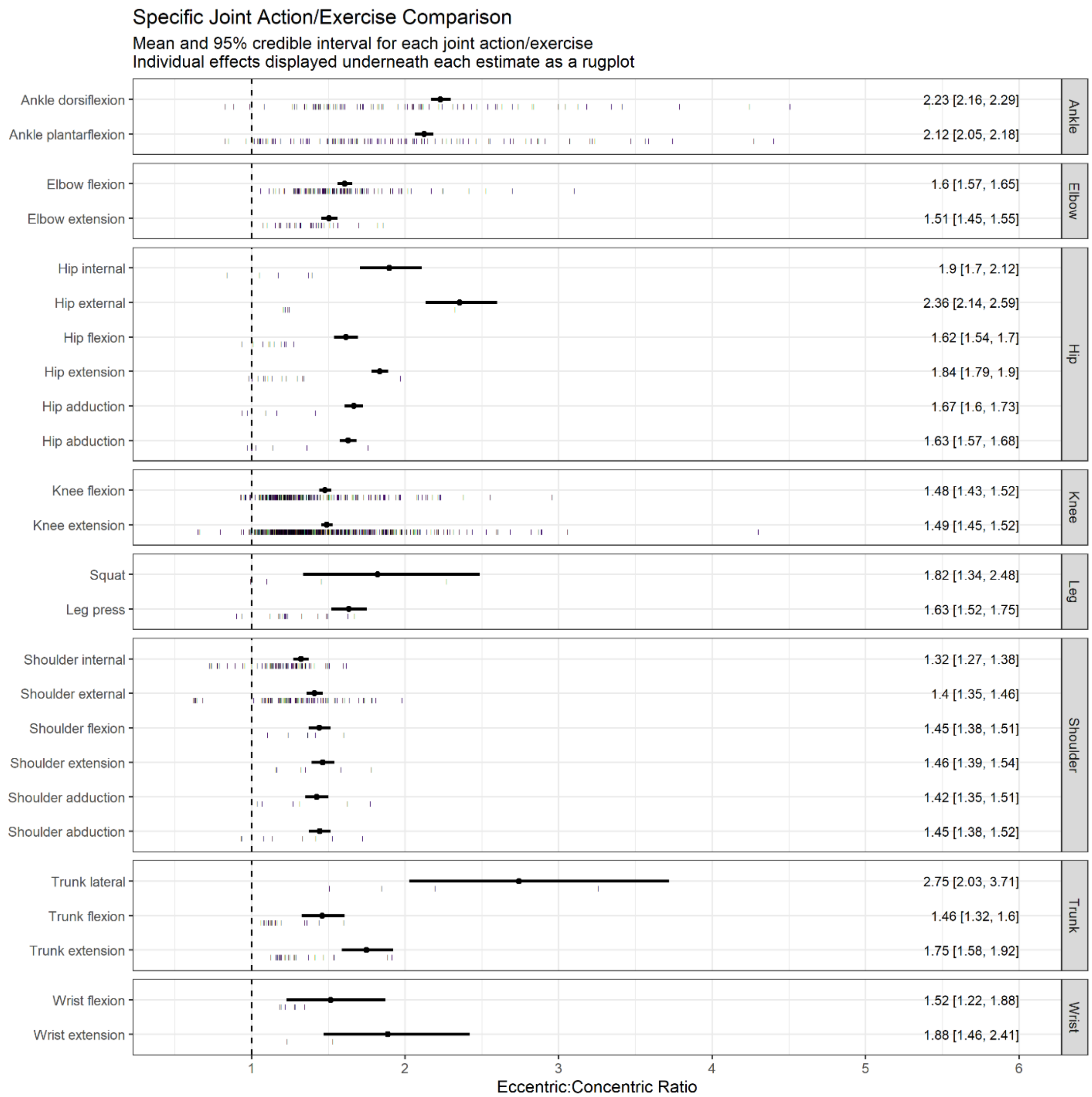

Figure 2. Eccentric:concentric (ECC:CON) strength ratios by joint action/exercise. Mean and 95% credible intervals are shown as the black circle and connected horizonal lines, respectively, with individual effects displayed as vertical dashes below each estimate as a rugplot.

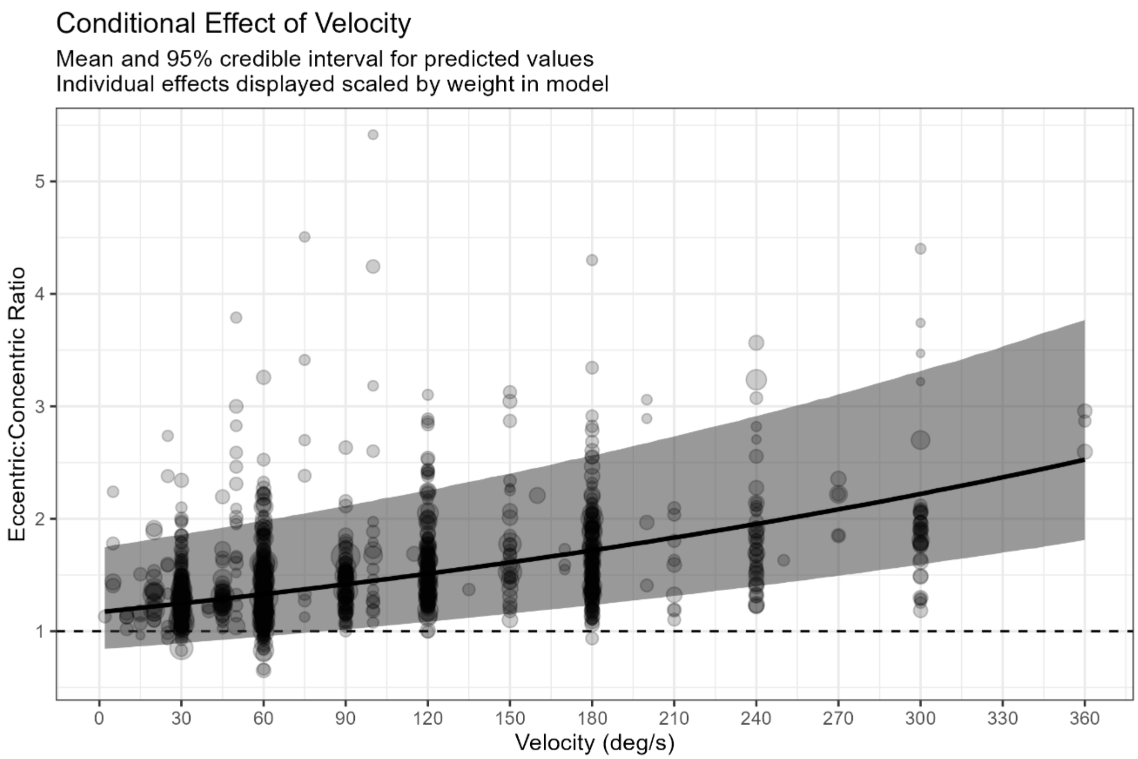

Figure 3. Eccentric:concentric (ECC:CON) strength ratios by test velocity. Mean and 95% credible intervals are shown as the black line and grey shaded area, respectively, with individual effects as circles with the sizes of the circles scaled to weighting in the model.

4.0 Discussion

The purpose of this meta-analysis was to determine the magnitude of the ECC:CON strength ratio and explore if sex, age, joint actions/exercises, and movement velocity impact it. We found consistent evidence that ECC strength is greater than CON strength. Across 290 studies, the main model estimate for the ECC:CON strength ratio was 1.40. Thus, ECC muscle strength is generally ~40% greater than CON muscle strength. However, the ECC:CON strength ratio is impacted by movement velocity and age and to a lesser extent sex. No difference in the ECC:CON strength ratio was observed between upper-body and lower-body joint actions/exercises generally speaking, but exploratory analysis suggested heterogeneity in the ECC:CON strength ratio across specific joint actions/exercises.

4.1 Sex

The ECC:CON strength ratio was slightly greater in women (1.46) than men (1.39). The reason for this slight sex difference appears to be that the magnitude of the sex difference in muscle strength is greater in CON than ECC muscle actions [38]. One explanation for this result might be that men participate in muscle-strengthening activities more regularly than women [38]. Such activities typically involve lifting a constant load, and this load will represent a greater percent of the CON than ECC 1RM. This might then provide disproportionately greater potential for increasing CON than ECC muscle strength considering specificity in strength gains. A potential practical implication of this finding is that if an exercise professional chooses to prescribe ECC overload as percent of the CON 1RM, then the multiplication factor for this computation might need to be slightly higher for women than men.

4.2 Age

The ECC:CON strength ratio was greater in older adults (1.65) than younger adults (1.38). The likely reason for this result is that ECC strength is better preserved with aging than CON strength [7, 39, 40]. Also, as aging research usually involves examination of CON rather than ECC strength, this helps to explain why men exhibit relatively greater reductions in strength (i.e., CON strength) in both cross-sectional and longitudinal aging research [41, 42]. In one longitudinal study of older adults, reductions in CON strength of muscles about the elbow were 2% per decade in women but 12% per decade in men [41]. A potential practical implication of this finding is that if an exercise professional chooses to prescribe ECC overload as percent of the CON 1RM, then the multiplication factor for this computation might need to be higher for older adults than younger adults.

4.3 Joint action/exercise

In the current analysis, muscle strength measurements acquired from joint actions/exercises about the wrist, elbow, and shoulder were combined into one upper-body ECC:CON strength ratio. Similarly, strength measures acquired from joint actions/exercises about the ankle, knee, and hip were combined into one lower-body ECC:CON strength ratio. The ECC:CON strength ratio was generally similar between the upper-body (1.43) and lower-body (1.40). However, exploratory analysis revealed heterogeneity between some joint actions/exercises. We consider this analysis exploratory, in part, because of a relative lack of ECC versus CON strength data for some joint actions/exercises. Indeed, this is reflected in the imprecision in estimates for some joint actions/exercises (e.g., squat, trunk lateral flexion, hip internal and external rotators, and wrist flexors and extensors). The knee extension was the joint action/exercise studied most frequently, with 518 effects, and this was more than double the next most frequently studied joint action/exercise (i.e., knee flexors, 205 effects) (Table 3). Nevertheless, heterogeneity in the ECC:CON strength ratio between specific joint actions/exercises appears to exist. Future research should systematically explore different joint actions/exercises with large samples to obtain more precise estimates of their ECC:CON ratios. Moreover, 98% of ECC:CON strength ratios came from tests of isokinetic muscle strength, with few researchers attempting to measure both ECC and CON 1RM with free weights, weight stack machines, or plate-loaded machines. The ECC 1RM is often impractical to examine given the design of most contemporary resistance exercise equipment. However, emerging resistance exercise technologies, discussed briefly in Section 4.5., could make evaluation of maximal ECC strength safer and more feasible in coming years. Such machines might then be used to establish ECC:CON muscle strength ratios for various joint actions/exercises.

Table 3. Number of effects for each joint action/exercise

Joint Action/Exercise	No. Effects
Knee extensors	518
Knee flexors	205
Ankle plantarflexors	106
Elbow flexors	106
Shoulder external	84
Ankle dorsiflexors	81
Shoulder internal	70
Elbow extensors	30
Trunk extensors	23
Trunk flexors	17
Leg press	16
Hip extensors	13
Hip flexors	10
Shoulder abductors	8
Hip abductors	7
Hip external	6
Shoulder adductors	6
Shoulder extensors	6
Shoulder flexors	6
Wrist flexors	6
Hip adductors	5
Hip internal	5
Squat	5
Trunk lateral	4
Wrist extensors	2

4.4 Velocity

The factor that impacted the ECC:CON strength ratio the most was movement velocity. The ECC:CON strength ratio was largest at fast velocities and smallest at slow velocities. The greater ECC:CON strength ratio at faster velocities is due primarily to the substantial reduction in CON phase torque that occurs at faster velocities. Our analysis revealed a log-linear relationship between test velocity and the ECC:CON ratio such that the ratio increased 0.21% for every 1°/s increase in velocity. A potential practical implication of this finding is that resistance exercise technologies that can control ECC and CON phase velocities independently can account for such differences to optimize force generation during the ECC and CON phases.

4.5 Implications overview

Historically, ECC resistance exercise has been difficult to prescribe because of limitations of free weights and weight machines. "Releasers," which dispose of a proportion of the eccentric load after the ECC phase, have been used with free weights and weight machines to overcome such limitations [18]. However, "releasers" can be difficult to use beyond the first repetition. The lack of feasibility to implement ECC resistance exercise with such equipment also explains why, in the current review, so few studies assessed ECC 1RMs, i.e., isoinertial load testing. The lack of feasibility of using such equipment for ECC testing and training also explains why, in one survey, 23% of strength and conditioning coaches said inadequate equipment was the most significant barrier to implementation of ECC resistance exercise [43]. Moreover, in another survey, 57% coaches who had never prescribed ECC resistance exercise said the main reason was equipment inaccessibility [20]. Nevertheless, new exercise technologies have the potential to make ECC resistance exercise more accessible, safe, and feasible. Examples of such equipment include connected adaptive resistance exercise (CARE) machines [22], flywheels [44], and motorized isokinetic devices [45]. Other ECC resistance exercise machines also exist and have been reviewed by Tinwala et al. [17]. With such equipment, independent load prescriptions for the ECC and CON phases is sometimes possible. Thus, knowledge of ECC:CON strength ratios might be useful for coaches who use such equipment to prescribe ECC overload. Currently, coaches [20] and researchers prescribe ECC loads ranging from 1.05 to 2.0 times the CON 1RM or CON training load (Table 1). Results from the current analysis suggest factors such as velocity, joint action/exercise, age, and to a lesser extent sex warrant consideration when determining how much ECC overload to prescribe in athletic, clinical, and research settings. For example, if ECC overload is computed based on CON 1RM, then higher multiplication factors are likely necessary for older than younger adults and for faster than slower velocities. New exercise technologies have potential to allow for isokinetic exercise and independent control of ECC and

CON resistances in non-laboratory environments. Isokinetic modes in such machines might account for the impact of velocity on force. To allow participants to generate their greatest CON forces, slow movement velocities would be necessary. For the ECC phase, more leniency could be provided, as force output in the ECC phase is less impacted by velocity.

5.0 Conclusion

Researchers have known for many decades that ECC strength is greater than CON strength. However, prior to the current review, the magnitude of this strength difference, and the factors that impact it, had never been submitted to review and meta-analysis. We report a main model estimate for the ECC:CON strength ratio of 1.40. However, the ratio is higher at faster than slower movement velocities and in older adults than younger adults. The ratio is also slightly higher in women than men. The ratio does not differ between upper- and lower-body muscles generally speaking, but an exploratory analysis indicated that there is likely heterogeneity in ratios across different joint actions/exercises. Further systematic study will be necessary to identify more precise estimates of exercise-specific ECC:CON strength ratios. Exercise practitioners can use the ECC:CON ratios discovered in the current analysis to guide prescriptions of ECC overload in athletic, clinical, and research settings.

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Data and Supplementary Material Accessibility
All materials, data, and code are available on the Open Science Framework project page for this study https://osf.io/8vt9h/

Author contributions
JLN wrote the first draft of the manuscript. JLN performed the literature search. JS performed the meta-analyses. All authors were involved in the interpretation of the meta-analyses, read, revised, and approved the final manuscript.

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