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Repeatability and Specificity of Eccentric Force Output and the Implications for Eccentric Training Load Prescription

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ABSTRACT

Prescribing supramaximal eccentric (ECC) loads based on repetition maximum (RM), isometric (ISO) or concentric-only (CON) strength overlooks the possibility that individuals have a different tolerance for ECC exercise. To inform the prescription of ECC training regimes, this study implemented a test battery that included maximal accentuated-eccentric (ECC+), traditional coupled eccentric-concentric (TRAD) and two ISO conditions (90° and 120° knee-joint angle [ISO_{90} and ISO_{120}, respectively]). The study aimed to determine the repeatability and specificity of ECC+ force output and assess the methodological accuracy when using non-specific measures of strength to prescribe ECC+ training loads. Results show that the test battery was repeatable ($p > 0.05$, ICC > 0.95, CV: <5.8%) and force output was specific to each task; ECC+ (4034 ± 592 N) was higher ($p < 0.001$) than ISO_{90} (3122 ± 579 N) and TRAD (3574 ± 581 N), but less ($p < 0.001$) than ISO_{120} (6285 ± 1546 N). Although estimations of ECC+ strength were not different from observed ECC+ values ($p > 0.05$), estimations were associated with up to a 7% error. This investigation confirms that force output is task-specific, therefore prescribing ECC loads based on strength during another task will likely lead to discrepancies in intended and actual ECC exercise intensity. Consequently, using an ECC specific approach to assess ECC strength qualities will provide a more accurate platform to prescribe individualized ECC training programmes and a more definitive evaluation of ECC strength.

KEY WORDS: testing, evaluation, strength, task-specific, lengthening

INTRODUCTION

High intensity eccentric (ECC) exercise has been consistently demonstrated to confer superior neuromuscular adaptations in comparison to isometric (ISO) and dynamic (coupled eccentric-concentric or concentric-only, CON) training (3,19,24,27). This has been attributed to the greater mechanical loading that can be achieved when using ECC compared to CON and ISO modalities (29). Because of the greater intrinsic force producing capacity associated with ECC muscle actions, ECC training requires using heavy external loads and demands a very high exercise intensity. This is something that cannot be achieved during conventional exercise where the ECC portion of a lift is exposed to a sub-optimal load (35) as the ECC portion of the lift is not directly related to the individuals ECC maximal capacity. In order to optimally stimulate the neuromuscular system with ECC contractions, the training must involve loads that are considered ‘supramaximal’ (loads greater than one can tolerate concentrically or isometrically), which are used to present a more optimal ECC stimulus (34).

It is common practice for strength and conditioning practitioners, rehabilitation professionals and sports science researchers to prescribe supramaximal ECC loads and/or evaluate ECC performance grounded on repetition maximum (RM) strength tests, which are based on CON strength (1,2,6,8,9,13,22). This approach to load prescription however, overlooks task-specificity and the possibility that some individuals have a different tolerance for ECC exercise (26) versus other contraction types, despite a similar level of ISO or CON strength. Therefore, prescribing resistance exercise based on non-specific measures of strength could result in the athlete working at sub-optimal intensities (either too high or too low). Consequently, this is likely to decrease the efficacy of ECC training regimes and impede functional evaluations pertaining to the neuromuscular responses to an ECC stimuli. Ensuring that exercise prescription is accurate will not only enhance the effectiveness of ECC resistance training regimes, but it will reduce the risk of injury and prevent excessive training load. This is especially important in a high-performance context, when ECC training loads are likely to be extremely high.

In order to inform the prescription of ECC training loads and evaluation of muscle function under high intensity ECC conditions, this study implemented a test battery that included maximal accentuated-eccentric (ECC+), traditional coupled eccentric-concentric (TRAD) and two ISO conditions (90° and 120° knee-joint angle [ISO_{90} and ISO_{120}, respectively]) with the aim to; (1) determine the repeatability and specificity of ECC force output and, (2) assess the methodological accuracy when using non-specific measures of strength to prescribe ECC training loads. We hypothesised that force output would be task-specific, and force profiles would demonstrate inter-subject variability. Consequently, approaches that use non-specific measures of strength to prescribe ECC load would be associated with a degree of inaccuracy.

METHODS

Experimental Approach to the Problem

A within-subjects, repeated measures design was used to determine the repeatability and specificity of ECC+ force output compared to TRAD, ISO_{90} and ISO_{120} during a lower body, multi-joint movement. Subjects attended the laboratory on three separate occasions, separated by seven days. Following familiarization of the testing procedures during the first visit, strength assessments were performed during visit two and were repeated during visit three. Maximal force output during ISO_{90} and ISO_{120} was assessed within three efforts, for each task. Maximal force output during TRAD and ECC+ were assessed within five and six efforts, respectively. Testing for each muscle action was separated by 10 minutes (min) to allow sufficient recovery. The assessments were purposely performed in the following order; (1) ISO_{90} and ISO_{120}, (2) TRAD, and (3) ECC+ to ensure some level of incremental preparation was delivered in preparation for increasing loads.

Subjects

Twelve strength trained males (mean ± SD age, stature and body mass: 31 ± 6 years, 181.8 ± 3.6 cm and 87.6 ±7.9 kg, respectively) volunteered to participate in this study. Based on pilot work with a similar population using this instrument we calculated the smallest worthwhile change and typical error of 119 N and 116 N, respectively; with an α of 0.05 and at 80% power, a sample of not less than nine participants would be required. Subjects had 12 ± 9 years of resistance training experience and had a strength-power sport background e.g. rugby, combat, powerlifting, track and field. All subjects were free from musculoskeletal injury and did not have a history of cardiovascular disorders. Data collection took place during the off-season. For the duration of the study the volunteers were asked to avoid unaccustomed exercise and refrain from strenuous physical activity in the 48 hours prior to each assessment. They were instructed to attend each session in a well-hydrated and fed state, having abstained from alcohol in the preceding 24 hours. Additionally, they were asked to keep a consistent routine (nutrition, sleep and general exercise) in the days leading up to each testing session. All study procedures and requirements, including benefits and risks associated with the investigation, were outlined and discussed prior to taking part in any testing. Following this, the subjects provided written, informed consent using approved documentation. Ethical approval was granted by Northumbria University Research Ethics committee in accordance with The Declaration of Helsinki.

Procedures

Equipment and Instrumentation. All strength assessments were conducted on a custom-built 45° incline leg press machine (Sportesse, Somerset, UK) (14). Engineering modifications facilitate the performance of concentric, isometric and accentuated eccentric exercise. Operated via a pneumatic system, the leg press device facilitates the use of higher loads (up to 420 kg) during the eccentric phase of the exercise which then 'unloads' at the end ROM. This is achieved using reed switches which allows the user to return the carriage to the start position without the use of spotters or assistance. The isometric function operates via an integral locking mechanism that can secure the carriage at various positions along the machines framework. Instrumentation (sampling at 200 Hz) were attached to the foot carriages enabled the acquisition of the force output specific to each of mode of action. Raw data was exported from the data acquisition software (LabVIEW 6.1 with NI-DAQ 6.9.2, National Instruments Corporation, USA) into Microsoft Excel format (Microsoft Excel, 2010) and were analyzed offline.

Warm-Up. Prior to completing strength assessments, subjects completed a standardized warm using a cycle ergometer (Wattbike Pro, Wattbike Ltd., Nottingham, UK) pedaling at 80 rpm at 120 W for 5 min. Immediately following this, 5 min of dynamic mobility exercises were completed that targeted the trunk, hips and lower limbs. This was followed by 8, 6 and 4 repetitions of leg press exercise with a load equivalent to 70, 85 and 100% of body mass, respectively. Each set was separated by 2 min.

Isometric Force Assessment. To determine maximum ISO force output, the leg press foot carriage was secured at a position (verified by hand held goniometry) that allowed the subject to achieve either a 90° or 120° knee angle depending upon which test was being performed. For each ISO assessment, subjects completed two separate ISO preparations, one at 50% and one at 75% perceived effort, separated by 30 seconds (s) rest. Testing for each position consisted of 3 maximal, 5 s efforts interspersed by 3 min rest. Subjects were advised to inhale and brace their trunk before progressively building force ready to push as hard as possible, until instructed to stop. The same strong verbal encouragement was provided for all efforts. The trial with the greatest peak force was used for analysis. The knee joint angles used in this study were chosen as they are commonly used for isometric assessment (21,37). Additionally, the 90° angle was chosen as it reflected the portion of the leg press movement where force output is most restricted during both the TRAD and ECC+ assessments used in this study. The 120° angle was chosen, following preliminary testing, to provide an indication of the maximum force capacity of the individual in a much less restricted position. Critically, the chosen positions represented the habitual practice of professional strength and conditioning coaches that have used this instrument.

Coupled Eccentric-Concentric Force Assessment. This assessment consisted of both the lowering (ECC) and raising (CON) phases of the leg press exercise. The assessment determined the maximum weight that could be moved to the nearest 5 kg through the required range of motion for a single repetition. This was established within 5 attempts, each effort separated by 5 min. The speed of the preceding ECC descent was self-selected by the subject. However, the range of motion (ROM) was standardised to 90° of knee flexion that was verified during each effort using the adjustable reed switches integral to the instrument's framework, which provided an auditory signal when the ROM had been achieved. If full ROM was not achieved, then the effort was deemed a failed repetition and the effort was repeated after 5 min. The force data taken for analysis reflected the force of the external load that was being imposed on the subject and not the force exerted by the subject when the load is moving. This ensured that the measures of force were not influenced by movement velocity which could affect measurement stability between sessions. Additionally, this approach ensured practicality of the findings such that they can be interpreted by practitioners who do not have access to force plates on their instrument.

Eccentric Force Assessment. The aim of the eccentric force assessment was to determine the heaviest load that could be lowered under control for 5 s in a consistent manner throughout the pre-set ROM (10° - 90° knee flexion), preceding a lifting phase loaded with 50% TRAD (see above). The lifting phase was always loaded with 50% TRAD for all ECC+ efforts. To standardise the pace of the ECC phase, a custom-built LED strip with individually addressable LED's (WS2812, BTF Lighting Technology Co. Ltd) controlled by a development board (Elegoo Mega 2560 R3, Elegoo Inc. UK & Arduino 1.8.4) and custom written code was added to the instrument. The LED's light up in a gradual manner to create a light trail that the subject can follow, using a marker that is secured to the foot carriage. The length of the light trail (total number of LED lights) is pre-set to a distance that reflects the displacement that the foot carriage has to travel until the subjects knee reaches 90° angle. The first ECC+ effort was performed with a load which was equivalent to TRAD, which had been established in the previous assessment. Upon successful completion of an effort, a 5% increment in mass was added until the 5 s pace set by the LED lights could no longer be maintained. Inability to maintain the 5 s time under tension was deemed a failure. Following a failed effort subjects were given 5 min rest before attempting the load once more. In the event of a second failed attempt, force output associated with the preceding effort was used for analysis. Maximum was achieved within 6 efforts, each separated by 5 min.

Statistical Analyses

All data are presented as mean ± standard deviation. Hopkins spreadsheet for reliability (18) was used to calculate intraclass correlation coefficient (ICC), coefficient of variation (CV, %), including their 95% confidence intervals (CI) and typical error (TE). Thresholds for CV classification were *good* (≤ 5%) or *acceptable* (5-10%). A paired samples t-test was used to identify differences in force output between testing sessions (session 1 [S_1] and session 2 [S_2]) for each strength task (ECC+, ISO_{90}, ISO_{120} and TRAD). Data from S_1 and S_2 were pooled ($[S_1 + S_2]/2$). A repeated measures ANOVA followed by a Bonferroni *post-hoc* test was used to investigate differences in force output when comparing ECC+ to ISO_{90}, ISO_{120} and TRAD. These data were supported with Cohen's *d* effect sizes. ECC+ force output data was normalized to TRAD, ISO_{90} and ISO_{120} and expressed as a percentage. Pearson's correlation [*r*] and linear regression analysis were used to evaluate the strength of the relationships between ECC+ force output and TRAD, ISO_{90} and ISO_{120} force output and obtain equations used to estimate ECC+ force output. Residuals analysis was used to determine the absolute differences in observed and estimated ECC+ values for each data set. These data would inform about measurement bias (mean difference) and precision of the estimation (95% CI). A paired samples t-test was used to determine differences between observed and estimated ECC+ values. These data were supported with Cohen's *d* effect sizes. All data was checked for normal distribution using Shapiro-Wilk test of normality prior to conducting statistical tests. Analyses were conducted using SPSS (Version 24.0; SPSS Inc., Chicago, USA) unless it is stated otherwise. Alpha level (α) was set at $p \leq 0.05$, a-priori. All effect sizes were interpreted in accordance with Hopkins (17)

RESULTS

Shapiro-Wilk's test revealed that TRAD, ISO_{90}, ISO_{120} and ECC+ were normally distributed. Test-retest measurements were not significantly different ($p > 0.05$, $d < 0.2$). Reliability of the test battery was established (ICC > 0.95; CV < 6%; Table 1). Differences in force output between tasks were significant ($F_{1.1, 11.7} = 51.2$, $p < 0.001$, $d > 0.8$). Force output for ECC+ (4034 ± 592 N, 95% CI: 3658 - 4410) was greater ($p < 0.001$) than ISO_{90} (3122 ± 579 N, 95% CI: 2755 - 3490) and TRAD (3574 ± 581 N, 95% CI: 3204 - 3943), but significantly less ($p < 0.001$) than ISO_{120} (6285 ± 1546 N, 95% CI: 5302 - 7267).

INSERT TABLE 1 ABOUT HERE

When normalized, ECC+ force output equated to; 113.2 ± 6.3% (95% CI: 109.2 – 117.2), 130.4 ± 11.6% (95% CI: 123.1 – 137.8) and 66.8 ± 14.2% (95% CI: 57.8 – 75.8) of TRAD, ISO_{90} and ISO_{120}, respectively. These percentage differences were not consistent between individuals (Figure 1).

INSERT FIGURE 1 ABOUT HERE

There was a strong linear relationship between; ECC+ and ISO_{90} ($r = 0.88$, $p < 0.05$) and, ECC+ and TRAD ($r = 0.93$, $p < 0.05$). There was a moderate linear relationship between ECC+ and ISO_{120} ($r = 0.43$, $p > 0.05$). The mean difference between observed and estimated ECC+ force outputs were not different ($p > 0.05$; $d < 0.002$); ISO_{90}: -1.0 ± 277.3 N (95% CI: -157.9–155.9); TRAD: 0.1 ± 211 N (95% CI: -119.4–119.6) and ISO_{120}: -0.01 ± 534.4 N (95% CI: -302.4-302.3). Residual plots are presented in Figure 2.

INSERT FIGURE 2 ABOUT HERE

DISCUSSION

To inform the prescription of ECC training loads and evaluation of muscle function under high intensity ECC conditions, this study implemented a test battery comprising of ECC+, TRAD and ISO_{90} and ISO_{120} tasks with the aim to determine the repeatability and specificity of ECC+ force output and assess the methodological accuracy when using non-specific measures of strength to prescribe ECC training loads. This study found that ECC+ force output was repeatable, along with performance under the other components of the test battery. Specificity of ECC force output was demonstrated as force output during ECC+ was greater than force output during ISO_{90} and TRAD, but less than ISO_{120} due to the change in knee joint angle. Subjects presented individual tolerances to strength assessment. Hence, estimations of ECC strength derived from non-specific measures of strength were associated with a margin of error.

A specialised ECC assessment has been examined and strong evidence has been provided that the method used is reliable. The repeatability of ECC+ force output from the current study are consistent with previous findings for ECC strength parameters obtained using isokinetic tasks [ICC: 0.81-0.99 and CV: 4-13% (7,11,19,25,35)] and tasks using dynamic constant external resistance [ICC: 0.79-0.99 and CV: 2-13% (4,16,30,33)]. In the current study, the error associated with each strength task was equivalent to 3% of force output for TRAD, 4% of force output for ISO_{90} and ECC+, and 7% of force output for ISO_{120}. The current information could be used to aid the interpretation of changes in force output by allowing practitioners to gauge whether the changes are due to measurement variation or can be attributed to real change. That said, including more than 1 familiarization session, especially for the higher force generating tests, could reduce the error associated with all components of the test battery. However, this would require further investigation. Importantly, the outcomes of the ECC assessment were not dissimilar to the other more established components of the test battery. Overall, these data support that task-specific ECC+ assessment is a reliable means to assess ECC performance. This approach could be incorporated within a more global strength testing battery, akin to the current study, to create a profile of specific strength qualities which could serve to inform decision making regarding the training needs of the athlete.

The testing battery used in this study enabled the researchers to identify and compare absolute force output associated with different strength qualities during lower body, multi joint exercise. As expected, when matched for ROM, the magnitude of force output was higher during ECC+ compared to ISO_{90} and TRAD which differed by ~30% and ~13%, respectively. This is likely attributable to the unique mechanical and neural features associated with ECC muscle actions (10,12,15). The magnitude of force enhancement relative to ISO is in line with those previously reported (14,20,28,31). However, the magnitude of force enhancement relative to TRAD (~13%) appears modest compared to others (2,9,13,19,23). Yet this could be attributed to the use of constant external resistance, the difference in ECC phase duration, the targeted muscle groups, multi-joint versus isolated movement and the strength level of the subject population. Overall, these data support that force output is governed by mode of muscle action.

Conversely, changing the knee joint angle from 90° to 120° caused isometric force capacity to exceed ECC+ force output by a considerable amount (~56%). This magnitude is similar to the findings of Marcora and Miller (21) when comparing isometric force output on a horizontal leg press device at the same knee joint angles that were used in the current study. The heightened force output is attributable to the more mechanically advantageous joint-angle (32). Therefore, it should be taken into account that when using a constant external resistance, where the magnitude of the load is usually dictated by strength at the end ROM, it is unlikely to match the strength curve of the individual. Hence, greater muscle tension and exercise intensity may be offered by non-ECC exercise with partial ROM versus ECC+ exercise at a greater ROM. But practitioners should consider that the higher intensity offered is likely to vary in magnitude for different individuals depending on their strength capacity at a more partial ROM (Figure 1). At this point, it is not clear to what magnitude ECC+ force output would differ from ISO and/or TRAD under different knee joint-angle constraints, aside from 90° which was employed in the current study.

Subjects showed different force generating potential across the different strength tasks. The differences probably reflect the phenotypical expression of neural, biomechanical, muscular, mechanical and morphological response to the individual training history (26,36). When considering the performance of all subjects the disparity between highest and lowest ECC+ force output values showed to be as great as 22%, 37% and 51% when normalised to ISO_{90}, TRAD and $ISO_{120,}$ respectively. These data suggest that when using TRAD and ISO measures of strength to prescribe ECC+ training loads, the prescribed intensity will almost certainly be a mis-match of intended intensity and actual intensity for a number of individuals because the nature of the prescription method lacks task-specificity.

When investigating this matter further, the current investigation found that despite observing very similar estimated ECC+ values versus observed ECC+ data (< 1 N difference in group means) when using non-specific measures of strength to estimate ECC performance, the precision of the estimates was associated with a 3%, 4% and 7% margin of error for TRAD, ISO_{90} and ISO_{120}, respectively. When considering the performance of all subjects, the highest underestimations and overestimations were ~10% for ISO_{90}, ~11% for TRAD and ~18% for ISO_{120}. Overestimations in load prescription could increase the propensity of injury or induce overreaching and in extreme cases might add to the risk of overtraining (5), especially in a high-performance environment when ECC loads are likely to be very high indeed. Conversely, underestimations in load prescription result in suboptimal loads and inadequate strength development (5). These data provide evidence that using non-specific measures of strength to prescribe ECC+ training loads is likely to cause errors in predicting ECC strength that could result in athletes training at an inappropriate intensity to that intended. Therefore, to ensure accuracy when providing individualized training programmes, it would be prudent to use task-specific assessment for the prescription of training loads and evaluation of muscle function, under high intensity ECC conditions. Consequently, using a task-specific approach to assess ECC strength qualities, such as those presented in this study, will provide a more accurate platform to prescribe individualized ECC training programmes and a more definitive evaluation of ECC strength.

In this investigation a bespoke device was used to determine the application of strength testing for eccentric overload exercise prescription. Although it is unlikely that practitioners will have this same device in their own training environments, they will almost certainly have inclined leg press devices.

These data provide insight in to how these instruments can be used effectively to gain information on an athletes capabilities, and critically highlight the potential pitfalls of not using task-specific strength testing for ECC overload training. As a result, testing battery approach of a similar nature to that used in this investigation could be used for assessing a range of important strength qualities in athletes and to examine progression. These experimental data help inform the prescription and evaluation of muscle function, particularly under high intensity ECC conditions using a device and procedures that are translatable to an applied setting.

PRACTICAL APPLICATIONS

The data derived from this investigation serve to enhance our understanding of the specificity of force output, which is of particular importance in assessing and prescribing ECC load. The bespoke instrument used in this study has aided the investigation in to the force producing characteristics of an ECC overload exercise, to reveal that estimating ECC training loads using different (non-specific) contraction types of muscle strength has the potential to be riddled with a high degree of error. Importantly, this investigation highlights that ECC strength is not necessarily proportional to other modalities of strength. In other words, being particularly strong in isometric or concentric strength, might not translate to proportional ECC strength. Consequently, to provide a more accurate basis for task-specific strength evaluation and the subsequent prescription of heavy ECC training loads we strongly urge practitioners to consider the development of a direct method to assess maximum ECC strength qualities.

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FIGURE LEGENDS

Figure 1. Representation of the percentage difference in force output between ECC and; ISO_{90}, TRAD and $IS0_{120}$ for each subject. Grey bars represent mean difference compared to ECC strength.

Figure 2. Absolute differences in observed and estimated ECC force output values derived from; (A) ISO_{90}, (B) TRAD and (C) ISO_{120} measures of strength. Dotted line represents calculation bias (mean difference). Solid lines represent calculation precision (95% confidence intervals).

TABLE LEGENDS

Table 1. Test-retest reliability statistics

Table 1. Test-retest reliability statistics.

Assessment Method	**Session No.**	**Mean Force (N)**	**SD (N)**	**95% CI (Lower-Upper)**	**Sig. (*p*)**	**ES (*d*)**	**CV (%)**	**95% CI Lower-Upper**	**ICC**	**95% CI Lower-Upper**	**TE (N)**
ISO$_{90}$	1	3171.4	624.4	2774.7 - 3568.1	0.06	0.17	3.76	2.65 - 6.46	0.97	0.90 - 0.99	113.05
	2	3073.5	541.9	2729.2 - 3417.8							
TRAD	1	3603.8	627.9	3204.9 - 4002.7	0.13	0.10	2.55	1.80 - 4.37	0.98	0.93 - 0.99	90.70
	2	3543.7	538.4	3201.6 - 3885.8							
ECC	1	4088.3	641.8	3680.5 - 4496.1	0.12	0.18	3.84	2.70 - 6.61	0.95	0.84 - 0.99	156.37
	2	3979.7	560.4	3623.7 - 4335.8							
ISO$_{120}$	1	6399.5	1587.2	5391.1 - 7408.0	0.20	0.15	5.77	4.05 - 9.99	0.96	0.87 - 0.99	414.97
	2	6170.2	1560.4	5178.7 - 7161.6							

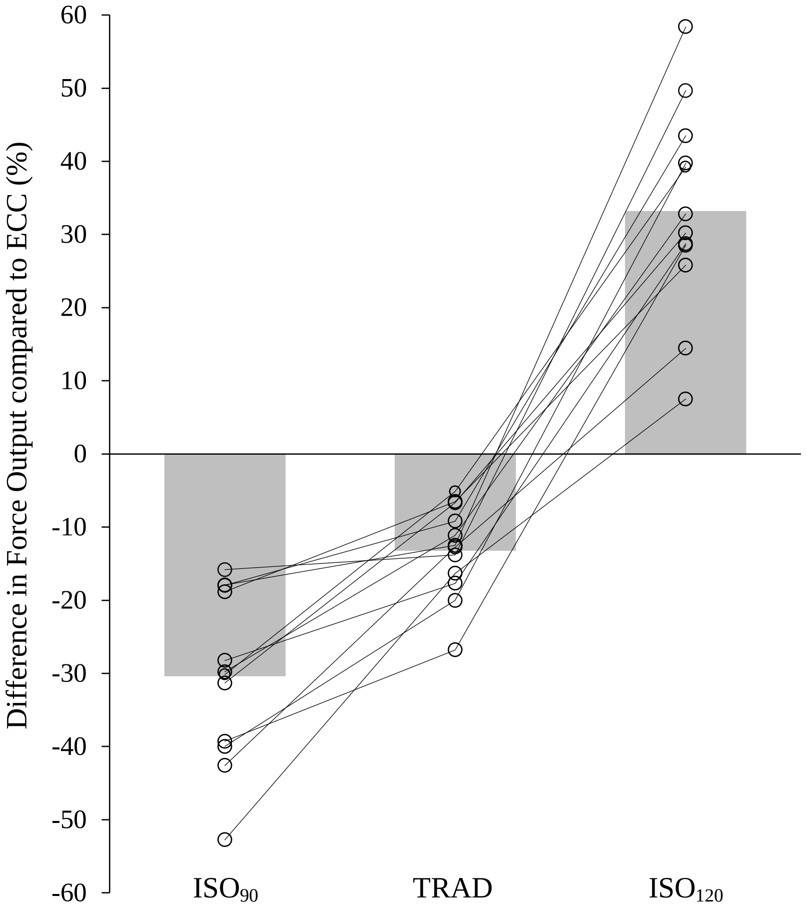

Figure 1. Representation of the percentage difference in force output between ECC and; ISO_{90}, TRAD and $IS0_{120}$ for each subject. Grey bars represent mean difference compared to ECC strength.

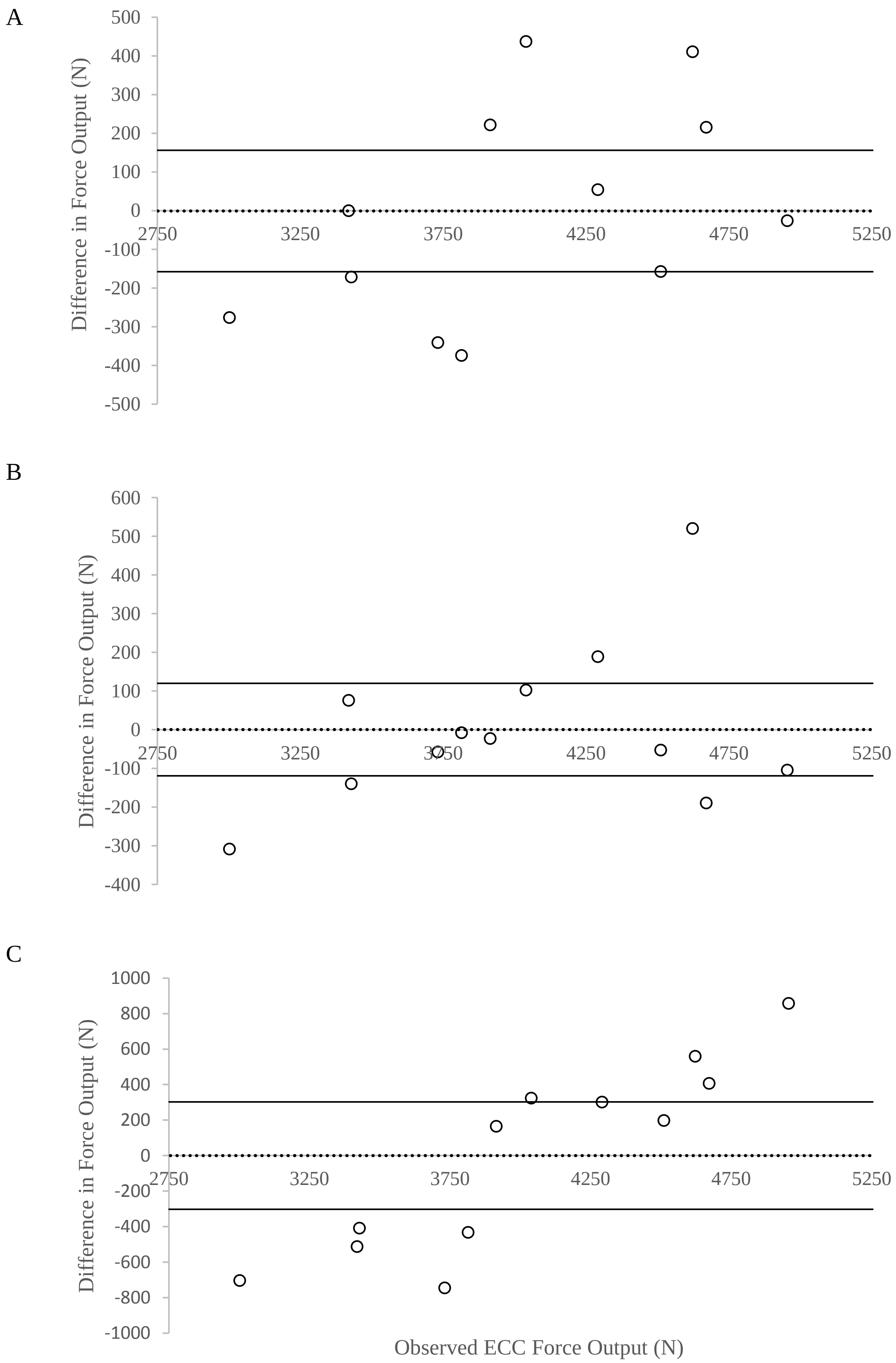
A
Difference in Force Output (N)
500
400
300
200
100
0
-100
-200
-300
-400
-500
2750
3250
3750
4250
4750
5250
B
Difference in Force Output (N)
600
500
400
300
200
100
0
-100
-200
-300
-400
2750
3250
3750
4250
4750
5250
C
Difference in Force Output (N)
1000
800
600
400
200
0
-200
-400
-600
-800
-1000
2750
3250
3750
4250
4750
5250
Observed ECC Force Output (N)

Figure 2. Absolute differences in observed and estimated ECC force output values derived from; (A) ISO_{90}, (B) TRAD and (C) ISO_{120} measures of strength. Dotted line represents calculation bias (mean difference). Solid lines represent calculation precision (95% confidence intervals).