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Long-Term Strength Adaptation: A 15-Year Analysis of Powerlifting Athletes

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Abstract

Latella, C, Teo, W-P, Spathis, J, and van den Hoek, D. Long-term strength adaptation: A 15-year analysis of powerlifting athletes. *J Strength Cond Res* XX(X): 000–000, 2020—Strength is a fundamental component of athletic performance and development. This investigation examined the long-term strength development of powerlifting (PL) athletes. The rate of strength gain/day was assessed in 1897 PL athletes (F = 626, M = 1,271) over a 15-year period (2003–2018). Independent T-tests explored sex differences in baseline absolute (kg) and relative strength (kg·body mass^{-1} [bm]) recorded from the first competition, and strength gain/day (kg·d^{-1}). Analyses based on initial strength quartiles were conducted using one-way analysis of variances with significance set at $p < 0.05$. Bivariate correlational analysis tested for relationships between strength gain/day and baseline strength, the number of competitions, and mean days between competitions. Males had greater absolute (M: 513.3 ± 99.8 kg, F: 289.4 ± 55.7 kg, $p < 0.001$) and relative (M: 5.89 ± 1.04 kg·bm^{-1}, F: 4.27 ± 0.85 kg·bm^{-1}, $p < 0.001$) strength at baseline. Overall, strength gain/day (F: 0.12 ± 0.69 kg·d^{-1}, M: 0.15 ± 0.44 kg·d^{-1}, $p = 0.318$) was similar between sexes. However, the strongest males showed a lower rate of strength improvement (0.102 kg·d^{-1}) compared with least strong males (0.211 kg·d^{-1}), $p = 0.010$. No differences were observed across quartiles for females. Correlational analyses revealed significant but weak negative relationships between strength gain/day and the mean days between competitions for females ($r^2 = -0.120$, $p = 0.003$) and males ($r^2 = -0.190$, $p < 0.001$). Similar relationships were observed for baseline strength ($r^2 = -0.073$, $p = 0.009$) and the number of competitions ($r^2 = -0.111$, $p < 0.001$) for males. The results suggest similar strength adaptation between sexes. The strongest males improve more slowly, possibly due to a ceiling effect. Collectively, the findings provide novel evidence of real-world long-term strength adaptations that may be particularly useful to understand athlete development, to aid periodized programming, and to benchmark strength over time.

Key Words: performance analysis, sport, resistance training, males, females

Introduction

Muscular strength is a fundamental component of long-term athlete development that aims to improve physical tolerance, facilitate performance, and reduce injury risk during competition (14,15,20,44). Subsequently, a large proportion of athlete training programs are dedicated to improving muscular strength characteristics. In team-based field and endurance sports, muscular strength positively impacts jump, sprint, and change of direction performance and correlates with sport-specific technical skills (27,44,48). However, in strength-dominant sports (e.g., powerlifting [PL] and weightlifting), muscular strength has a direct relationship with competition performance (30,31,43). Despite the importance of muscular strength, evidence of longitudinal strength adaptations in competitive athletes remains somewhat limited (3–5,16,23,24,34).

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Although strength improves rapidly at the onset of resistance training (RT) for novice individuals, the rate of improvement diminishes over time (46). In addition, general population RT research, and that not orienteered toward sport-specific or maximal strength development, is unlikely to reflect typical PL practice as during training PL athletes are required to develop specific maximal strength that is then expressed during competition. Thus, several factors should be considered in the translation of general RT research to athletic populations. For example, a number of studies have used machine-based, isolated movement tasks or a single-exercise regime to investigate RT strength adaptations (see Ref. 10,19 for examples). Moreover, while some authors have used periodized programs that may reflect typical PL practice (12,26), these studies along with other more general RT interventions (13,35) are typically 16 weeks or less in duration. Longer RT interventions (≥1 year) have been conducted; however, these are often based on untrained or older individuals (38,41) and youth athletes (39), potentially limiting the translation to high-performance sport. Therefore, comprehensive longitudinal evidence is required to add to the understanding of long-term strength development in athletes and to aid planning and periodization strategies.

In many sports, the required proficiency of several physical and physiological characteristics does not allow for strength development to be studied without the influence of other concurrent training modalities. For example, concurrent training including combined endurance and RT may negatively impact strength adaptations (17,22). Longitudinal evidence in team-based collision sports reports strength increases of approximately 6.5–11.5% and 22–23% over a 2- and 10-year period, respectively, in elite rugby players (3,4). However, the authors acknowledge that factors such as starting strength level and changes in lean muscle mass may negatively and positively influence strength adaptations, respectively. In comparison, strength sports offer a unique platform to investigate whole-body muscular strength development with minimal interference effects. In weightlifting, for example, adaptations to 1–2 years of strength training demonstrates an increase of 2.9% in competition total (24) and a nonsignificant 3.5% increase in isometric knee-extension force (23) in elite athletes. However, long-term adaptations in PL athletes and more specific changes (e.g., per day) are yet to be explored. To date, cross-sectional PL research has evaluated training practices (21,36,45), competition performance data (6,9,36), factors that may influence injury, and the prevalence of injury (1,8,28,40,42), lift kinematics (25), anthropometrics (29), and cross-sectional analyses of sex and competition-level differences in strength performance (30,31). Despite these studies, there is limited evidence regarding strength adaptation in PL athletes (13,26), especially over the longer term. Moreover, it is unclear how intrinsic (e.g., sex, starting strength level) and extrinsic (e.g., time between competitions and length of time competing) factors impact the rate of strength adaptation over time in powerlifters.

The purpose of this investigation was to analyze the rate of muscular strength improvements in competitive PL athletes. Specifically, we sought to investigate the rate of strength gain (per day) in both male and female powerlifters over a 15-year period. We hypothesised that (a) athletes with a lower starting strength would gain strength more quickly, and (b) males would gain strength faster than females. The results of this investigation are intended to provide comprehensive and novel information regarding long-term strength changes in competitive PL athletes. The findings are expected to have practical implications for both coaches and athletes and translate to other sports where strength forms an integral component of athletic development and performance.

Methods

Experimental Approach to the Problem

We collated available PL competition records from March 1, 2003, to May 20, 2018, that was extracted publicly from the Powerlifting Australia database (www.powerliftingaustralia.com).

Subjects

Data were collated from a total of 521 Powerlifting Australia sanctioned "raw" competitions from 2003 to 2018. Four thousand three hundred and seven competitor results were then screened for inclusion, and a total of 626 female and 1,271 male (final n = 1897) competitor results from Junior, Open, and Masters categories were included in the analysis. Specifically, raw Powerlifting Australia competitions permit the use of approved knee sleeves and a lifting belt only. All competitors and parent guardians consent to data use at the time of membership. The age of competitors at baseline was 26.8 ± 8.9 years, range: 15–74 years, and 30.6 ± 10.19 years, range: 14–77 years, for males and females, respectively. However, age data were only available at baseline for 69% of male and 82% of female competitors. The body mass of individuals at baseline was 88.7 ± 17.3 kg, range: 52.0–187.5 kg, and 69.1 ± 15.2 kg, range: 39.3–155.9 kg, for males and females, respectively. Subject characteristics were measured mean ± *SD*. Approval for this analysis was granted by the Edith Cowan University Human Research Ethics Committee (project no. 21408).

Procedures

Performance data were extracted for all athletes from each competition by taking the "total" score calculated as the highest successful weight lifted out of 3 attempts for the squat, bench press and deadlift, respectively, and used for further analysis. At least one successful lift out of the 3 attempts for each of the squat, bench press, and deadlift was required to record a total score during competition. Of the initial 4,307 competitors, individuals who competed: (a) only once, (b) in bench press or deadlift only competitions, (c) in equipped competitions (i.e., those that permit the use of knee wraps, squat, and bench suits), (d) or those who failed to record at least 2 "total" scores from separate competitions were excluded. In addition, database errors were removed by manually screening and determination of outliers. Individual competitor results with incomplete strength data were also removed. Starting relative strength was expressed for both males and females, regardless of age and calculated using the formula: First "total" competition scores (kg)/first competition body mass (kg). Competitors were then stratified into starting strength quartiles for each sex. Quartile 1 (Q1) indicated competitors with relative strength in the bottom 25% at baseline, while quartile 4 (Q4) indicated competitors with the highest relative strength at baseline. Quartile 2 (Q2) and quartile 3 (Q3) represented the 26th–50th percentile and 51st–75th percentile, respectively. In addition, the rate of strength gain per day was calculated using the following formula: (maximum total − first total)/total days competing, where "maximum total" is the total score in kilograms recorded from the competitor's maximum recorded competition total and "first total" is the first recorded total score in kilograms for the competitor during the period 2003–2018. This approach was chosen for several reasons. First, it provides a more realistic representation of the strength gained for each athlete over the period of the entire analysis. Second, it ensures that artificially inflated strength gain values (e.g., largest increase occurring between competition 1 and 2) are accounted for and do not significantly influence or bias the final result.

Statistical Analyses

One-way analysis of variances with Tukey post hoc analysis was conducted for variables where more than 2 groups were compared. Independent-samples T-tests were used to perform comparisons between males and females. Relationships between baseline strength, the total number of competitions, mean days between competitions, and strength gain/day were assessed using bivariate correlational analysis with tests for 2-tailed significance. Results are reported as r- and p-values, and mean ± *SD* (unless

Table 1
Male and female absolute and relative strength characteristics.

	Females, $n = 626$	Males, $n = 1,271$
Absolute strength		
First	289.4 ± 55.7	513.3 ± 99.8*
Maximum	322.5 ± 61.1	562.2 ± 104.8
Final	315.7 ± 61.2	549.6 ± 106.9*
Relative strength		
First	4.27 ± 0.85	5.89 ± 1.04*
Maximum	4.68 ± 0.98	6.25 ± 1.07*
Final	4.61 ± 0.98	6.16 ± 1.10*
Strength gain/day (kg)	0.12 ± 0.69	0.15 ± 0.44
Strength gain/year (kg) extrapolated	43.80	54.75

"Max' indicates highest obtained value over entire data analysis period while "final" indicates value at the athlete's last competition during the data collection period.
*$p < 0.001$.

otherwise indicated). Significance was set at $p \leq 0.05$ for all statistical analyses. All analyses and calculations were performed using SPSS v.25 (IBM Statistics) and Microsoft Excel (version 2013; Microsoft Corporation, Redmond, WA).

Results

Descriptive Statistics

Mean participation over the data collection period was 3.7 ± 2.6 (range 2–25) competitions for males, and 2.7 ± 2.6 (range 2–32) competitions for females. The mean time between an athlete's first and final competition was 642 ± 609 days and 582 ± 565 days for males and females, respectively.

Sex Differences

Total scores (first and final) (Figure 1A, B) and relative strength (first and final) (Figure 2A, B) differed between males and females (all $p < 0.001$) (Table 1). No difference was observed for strength gain/day between sexes, $p = 0.318$. Individual examples of changes in total scores, relative strength, and strength gain/day are shown in Figure 3A–C (female) and Figure 3D–F (male), respectively.

Strength Changes

An increase in total score (final total compared with first total) was observed for all quartiles (all $p < 0.001$) in both females and males (Table 2). No differences were observed between the strength quartiles for strength/day in females, $p = 0.686$ (Table 3 and Figure 4A). However, males in the highest quartile (Q4) showed a slower rate of strength adaptation compared with males in Q1 ($p = 0.009$) (Table 3 and Figure 4B).

Correlations

Bivariate correlational analyses revealed weak but significant negative relationships for the mean days between competitions and strength gain/day in males and females (Table 4). Significant weak relationships were also observed between maximum strength gain/day and baseline strength and the number of competitions for males. Further within quartile analyses demonstrated negative weak, but significant correlations (Q1: $r = -0.116$, $p = 0.038$) and positive weak correlations for (Q4: $r = 0.160$, $p = 0.004$) males based on starting strength and strength/gain per day. No significance was observed in females.

Discussion

The aim of this study was to analyze changes in muscular strength of PL athletes over time. Specifically, we investigated the rate of strength gain in 626 female and 1,271 male PL athletes over a collective 15-year period. Overall, the results suggest that the rate of strength gain does not differ between males and females, despite absolute and relative strength differences between the sexes. No differences in the amount of, or average days between competitions were observed between sexes. A slower rate of strength adaptation was observed for the strongest (Q4) compared with least strong (Q1) males. No differences were found in the rate of strength adaptation for females with different baseline strength levels (Q1-Q4). The findings are, to the best of our knowledge, the first to provide information regarding strength improvements over time in a large cohort of competitive PL athletes of both sexes. The results are expected to help understand long-term athlete development and be particularly useful for

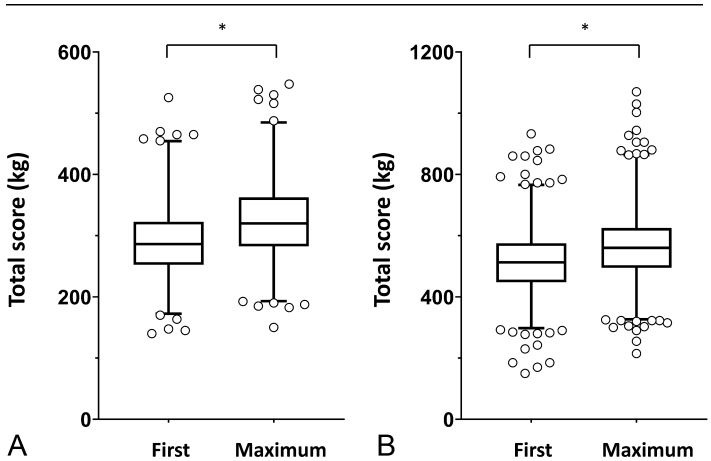

Figure 1. Data for (A) females and (B) males. Lines indicate range (first–99th percentile), and individual data points indicate athlete results outside of these percentiles. *Significant difference ($p < 0.001$) between totals.

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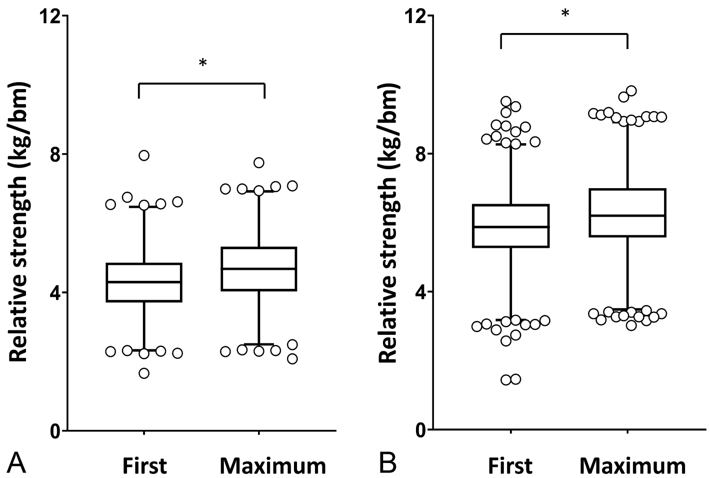

Figure 2. Data for (A) females and (B) males. Lines indicate range (first–99th percentile), and individual data points indicate athlete results outside of these percentiles. *Significant difference ($p < 0.001$) between totals.

strength and conditioning professionals working with strength athletes. The findings may also provide a platform to assess athletes' strength development and to benchmark progress over time.

Overall, the analysis revealed a similar rate of strength gain between competitors with different baseline strength levels. However, males in the strongest quartile (Q4) showed a slower rate of strength adaptation (0.102 kg·d^{-1}) compared with those in lowest (Q1) strength quartile (0.211 kg·d^{-1}). The mean number of days strength was assessed over did not differ between quartiles and, thus, is unlikely to account for this discrepancy. Although these results do not support our original hypothesis, there are several potential factors that may, at least in part, explain these results. In particular, a reduction in the rate of performance adaptations in strength and power athletes is commonly observed with continued training (34). For example, the rate of strength gain being slower in the strongest males may potentially be due to a ceiling effect. However, this effect was not observed in the strongest females and reasons for this observation are speculative at this stage. In addition, although we cannot ascertain whether athletes in quartile 1, that is the least strong athletes, were considered "novice" resistance trainees, our previous research suggests that less strong PL athletes likely compete at the local level (31) and, thus, may not be considered "elite" or "expert." However, it can be reasonably assumed that they are further away from reaching their maximal strength potential. Hence, although outside the scope of this immediate investigation, we suggest that more specific research is required into the intrinsic or extrinsic factors that may cause the strongest males to gain strength more slowly. Based on these findings, strength and conditioning professionals may be able to use this information to predict progressive adaptations in athletes' strength despite differences between individuals at baseline.

The results also showed that the rate of strength adaptation did not differ between males and females. Although this is in contrast

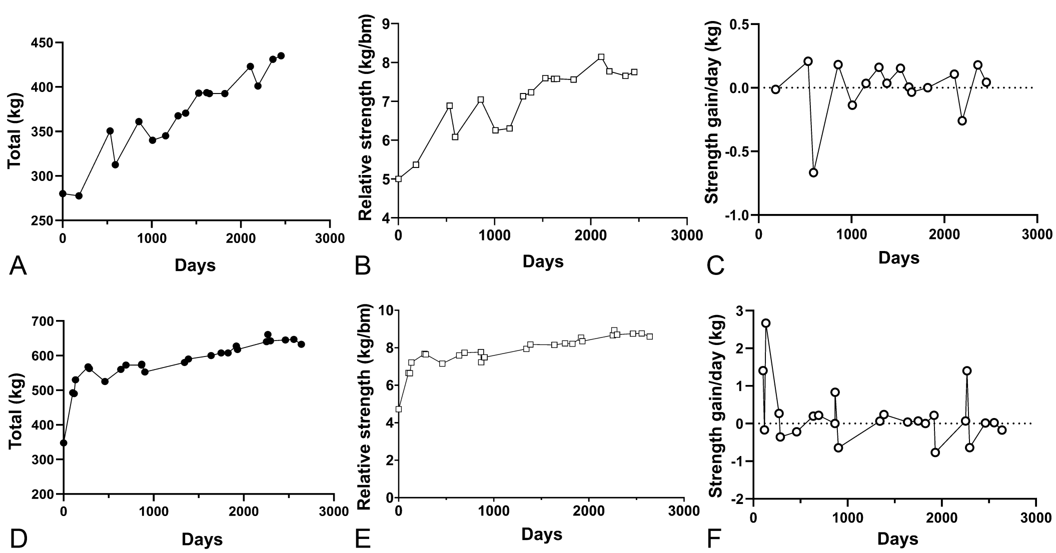

Figure 3. Example of the change from a single female (A–C, respectively) and male (D–F, respectively) athlete. kg·bm^{-1} = kilograms per body mass.

Table 2
Displays the change in absolute strength scores for males and females (first and maximum total) across each strength quartile.

	Quartile	Total	Mean ± SD (kg)	Δ Maximum total − first total (kg)
Females	First	First	257.7 ± 56.6	36.9 ± 36.7
		Maximum	294.6 ± 67.3	
	Second	First	282.9 ± 52.7	34.3 ± 32.7
		Maximum	317.3 ± 59.1	
	Third	First	296.1 ± 46.1	29.5 ± 30.9
		Maximum	325.7 ± 53.5	
	Fourth	First	320.9 ± 47.7	31.4 ± 29.2
		Maximum	352.3 ± 49.3	
Males	First	First	448.6 ± 100.0	60.9 ± 64.6
		Maximum	509.6 ± 111.5	
	Second	First	507.9 ± 88.8	45.1 ± 46.6
		Maximum	552.9 ± 97.3	
	Third	First	532.2 ± 89.7	47.9 ± 44.0
		Maximum	580.2 ± 93.9	
	Fourth	First	564.5 ± 82.7	41.3 ± 49.6
		Maximum	605.8 ± 91.0	

to our original hypothesis, similar results (e.g., adaptations in strength and muscle thickness) have also been reported between sexes in previous literature (2,18). It should be acknowledged, however, that the previous studies were conducted in general populations, and so, a direct comparison is difficult. Although long-term analyses have been conducted in weightlifting athletes (23,24,34), this was either performed only in female athletes (34), or over a 1- to 2-year period (23,24). In male rugby athletes, strength gains of approximately 2.2–2.3% per year averaged over a 10-year period (4), and the 6.5–11.5% total increase observed over a 2-year period (3) is noticeably lower than the approximated 10.7% observed in the current study (refer to Table 1 for raw male values). However, this discrepancy may be attributed to many of the PL athletes in the current study being novices, competing on average for a shorter period, and/or the complex nature of rugby, which involves multimodal training, frequent competition, and collision with opponents, as compared to PL. Thus, to the best of our knowledge, this is the first study to report and compare changes in strength over a considerable period in PL strength athletes of both sexes. Collectively, although differences in baseline maximal strength can be expected between males and female PL athletes as observed in the current and previous studies (30), the magnitude of relative strength adaptation over time seems to be similar. Therefore, strength and conditioning professionals may consider this information in the assessment of, and goal setting or programming of male and female athletes' muscular strength over time.

Significant but weak relationships were observed for the strength gain/day and the mean days between competitions in both sexes. However, given the "weak" relationship, it is difficult to delineate if an increased temporality of competition is a limiting factor in the strength adaptations of PL athletes. As such, we can only speculate that less days between subsequent competitions may negatively affect strength improvements due to shorter training blocks and more frequent taper periods (21,37). In particular, in the current analysis, the mean days between competitions were 161 ± 139 and 145 ± 108 days for males and females. PL-specific strength has been shown to improve significantly during a 9-week (~63 days) training block (12) and thus suggests that the number of days between competitions in the current analysis is unlikely to be a major factor. However, although the study by Colquhoun et al. (12) used resistance-trained men, the strength level was arguably less than many competitive PL athletes, and therefore, it is unclear how the findings translate to the cohort of PL athletes in the current study. Significant but weak negative relationships were also observed between strength gain/day and baseline strength and the number of competitions. However, given these relationships are considered "weak," they are unlikely to explain the majority of variance and other potential factors may also require consideration based on the previous literature in athletes. For example, several studies have investigated the reliability and variability of competition performance (32,33). Specifically, Malcata et al. (32) reported a 1.7 and 3.3% within-individual variance in performance for male and

Table 3
Results of the analyses for males and females based on respective strength quartiles for each sex.

	Quartile	Relative strength (baseline)	Days competing	Strength gain/day (kg)	Strength gain/year (kg) extrapolated	Significance between quartiles
Females	First	3.17 ± 0.39	527 ± 530	0.097 ± 0.109	35.41	$F_3 = 0.540$, $p = 0.655$
	Second	3.98 ± 0.17	573 ± 527	0.080 ± 0.134	29.20	
	Third	4.55 ± 0.16	559 ± 572	0.144 ± 0.586	52.56	
	Fourth	5.35 ± 0.43	665 ± 623	0.168 ± 1.25	61.32	
Males	First	4.57 ± 0.60	588 ± 594	0.211 ± 0.355*	77.02	$F_3 = 3.407$, $p = 0.017$
	Second	5.58 ± 0.17	637 ± 614	0.137 ± 0.324	50.00	
	Third	6.19 ± 0.19	674 ± 575	0.161 ± 0.659	58.77	
	Fourth	7.19 ± 0.53	668 ± 650	0.102 ± 0.330*	37.23	

Significance column refers to analysis of the strength gain/day (kg) between quartiles for each sex. *Males in the fourth quartile were significantly lower compared with males in the first quartile ($p = 0.010$).

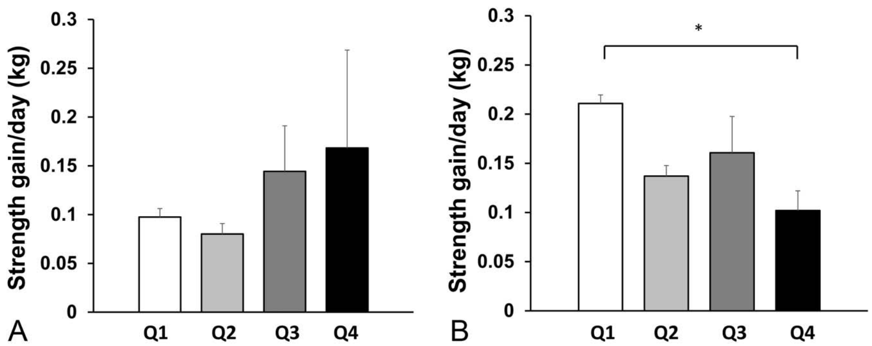

Figure 4. Data for (A) females and (B) males across all starting strength quartiles. *A significant difference between quartiles.

female weightlifters, respectively, with similar values reported by McGuigan et al. (33). Although the variability reported in these studies may be considerably low, it is also important to consider that most PL athletes in the current analysis were unlikely to be classified as "elite." Based on our previous work (31), we demonstrated that only 49% of 2137 PL competition results came from an elite (international) level of competition. In addition, poor performance during competition may result from missed lifts due to psychological factors and/or inadequate competition planning (11) and thus skew the results. Therefore, we suggest it is also important to acknowledge that other external factors unable to be controlled for in the current analysis may also affect "real-world" strength gains in athletes.

Finally, we acknowledge that several factors require consideration when interpreting the findings of this investigation. Given the nature of the study design, it was not possible to report more detailed information regarding training practices (e.g., consistency, training program used, and frequency). Moreover, we also acknowledge that potential injury or time away from the sport may impact an individual's strength improvement over time. Previous research (29) has also demonstrated the positive effect that anthropometric characteristics (e.g., muscle mass, segmental length, and girth ratios) can have on PL performance, and the ability to distinguish between stronger and weaker athletes. However, only body mass information was available in the data set used for the current study, and so, further conclusions cannot be drawn at this stage. Thus, ongoing research may also benefit from modeling anthropometric changes with strength improvements over time or to distinguish between individuals who may adapt more rapidly. In addition, given research has investigated acute responses to upper- and lower-body tasks (7,47) we suggest it is also worth investigating differences in strength adaption between the squat, bench press, and deadlift. Nevertheless, the results presented in this study provide a realistic representation of "real-world" strength adaptations outside of an interventional research setting. Although we suggest that future interventional studies studying long-term athlete development are required, this is, to the best of our knowledge, the first study to provide evidence in a large cohort of PL athletes over a significant period.

Table 4

Results of bivariate correlational analysis for males and females.

	Baseline strength	No. of competitions	Mean days between competitions
Maximum strength gain/day			
Females	$r = 0.027$	$r = -0.057$	$r = -0.120$
	$p = 0.496$	$p = 0.158$	$p = 0.003$
Males	$r = -0.073$	$r = -0.111$	$r = -0.190$
	$p = 0.009$	$p < 0.001$	$p < 0.001$

r^2 value represents the strength and direction of the relationship while p-value represents significance of the relationship.

Practical Applications

Based on the results, strength and conditioning professionals should consider tracking the development of strength athletes overtime, potentially using strength gain per day as an evaluation tool and metric. In addition, factors including sex and potentially starting strength level seem unlikely to have a large influence on the rate of strength gain over time. Coaches and strength and conditioning professionals could use the data presented in the current study to benchmark athletes' strength progress and appropriately plan and periodize RT in long-term development models.

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References

1. Aasa U, Svartholm I, Andersson F, Berglund L. Injuries among weightlifters and powerlifters: A systematic review. *BJSM* 51: 211–219, 2017.
2. Abe T, DeHoyos DV, Pollock ML, Garzarella L. Time course for strength and muscle thickness changes following upper and lower body resistance training in men and women. *Eur J Appl Physiol* 81: 174–180, 2000.
3. Appleby B, Newton RU, Cormie P. Changes in strength over a 2-year period in professional rugby union players. *J Strength Cond Res* 26: 2538–2546, 2012.
4. Baker DG. 10-year changes in upper body strength and power in elite professional rugby league players-the effect of training age, stage, and content. *J Strength Cond Res* 27: 285–292, 2013.
5. Baker DG, Newton RU. Adaptations in upper-body maximal strength and power output resulting from long-term resistance training in experienced strength-power athletes. *J Strength Cond Res* 20: 541–546, 2006.
6. Ball R, Weidman D. Analysis of USA powerlifting federation data from January 1, 2012—June 11, 2016. *J Strength Cond Res* 32: 1843–1851, 2017.
7. Belcher DJ, Sousa CA, Carzoli JP, et al. Time course of recovery is similar for the back squat, bench press, and deadlift in well-trained men. *Appl Physiol Nutr Metab* 44: 1033–1042, 2019.

8. Bengtsson V, Berglund L, Aasa U. Narrative review of injuries in powerlifting with special reference to their association to the squat, bench press and deadlift. *BMJ Open Sport Exerc Med* 4: e000382, 2018.
9. Bishop PA, Williams TD, Heldman AN, Vanderburgh PM. System for evaluating powerlifting and other multi-event performances. *J Strength Cond Res* 32: 201–204, 2018.
10. Brown N, Bubeck D, Haeufle DFB, et al. Weekly time course of neuromuscular adaptation to intensive strength training. *Front Physiol* 8: 329, 2017.
11. Coker NA, Varanoske AN, Baker KM, Hahs-Vaughn DL, Wells AJ. Predictors of competitive success of national-level powerlifters: A multilevel analysis. *Int J Perform Anal Sport* 18: 796–805, 2018.
12. Colquhoun RJ, Gai CM, Walters J, et al. Comparison of powerlifting performance in trained men using traditional and flexible daily undulating periodization. *J Strength Cond Res* 31: 283–291, 2017.
13. Colquhuon RJ, Gai CM, Aguilar D, et al. Training volume, not frequency, indicative of maximal strength adaptations to resistance training. *J Strength Cond Res* 32: 1207–1213, 2018.
14. Faigenbum AD, Myer GD. Resistance training among young athletes: Safety, efficacy and injury prevention effects. *BJSM* 44: 53–63, 2011.
15. Faigenbum AD, Myer GD. Pediatric resistance training: Benefits, concerns, and program design considerations. *Curr Sports Med Rep* 9: 161–168, 2010.
16. French DN, Gomez AL, Volek JS, et al. Longitudinal tracking of muscular power changes in NCAA Division I collegiate women gymnasts. *J Strength Cond Res* 18: 101–107, 2004.
17. Fyfe JJ, Bartlett JD, Hanson ED, Stepto NK, Bishop DJ. Endurance training intensity does not mediate interference to maximal lower-body strength gain during short-term concurrent training. *Front Physiol* 7: 487, 2016.
18. Galvao DA, Newton RU, Taaffe DR. Does sex affect the muscle strength and regional tissue mass response to resistance training in older adults?. *Int J Sport Health Sci* 4: 36–43, 2006.
19. Goto K, Nagasawa M, Yanagisawa O, et al. Muscular adaptations to combinations of high- and low-intensity resistance exercises. *J Strength Cond Res* 18: 730–737, 2004.
20. Granacher U, Lesinski M, Busch D, et al. Effects of resistance training in youth athletes on muscular fitness and athletic performance: A conceptual model for long-term athlete development. *Front Physiol* 7: 164, 2016.
21. Grgic J, Mikulic P. Tapering practices of Croatian open-class powerlifting champions. *J Strength Cond Res* 31: 2371–2378, 2017.
22. Häkkinen K, Alen M, Kraemer WJ, et al. Neuromuscular adaptations during concurrent strength and endurance training versus strength training. *Eur J Appl Physiol* 89: 42–52, 2003.
23. Häkkinen K, Komi PV, Alen M, Kauhanen H. EMG, muscle fibre and force production characteristics during a 1 year training period in elite weightlifters. *Eur J Appl Physiol Occup Physiol* 56: 419–427, 1987.
24. Häkkinen K, Pakarinen A, Alen M, Kauhanen H, Komi PV. Neuromuscular and hormonal adaptations in athletes to strength training in two years. *J Appl Physiol* 65: 2406–2412, 1988.
25. Hales ME, Johnson BF, Johnson JT. Kinematic analysis of the powerlifting style squat and the conventional deadlift during competition: Is there a cross-over effect between lifts? *J Strength Cond Res* 23: 2574–2580, 2009.
26. Joao GA, Evangelista A, Gomes JH, et al. Effect of 16 weeks of periodized resistance training on strength gains of powerlifting athletes. *J Exerc Physiol* 17: 102–109, 2014.
27. Keiner M, Sander A, Klaus W, Schmidtbleicher D. Long-term strength training effects on change-of-direction sprint performance. *J Strength Cond Res* 28: 223–231, 2014.
28. Keogh JW, Hume PA, Pearson S. Retrospective injury epidemiology of one hundred competitive Oceania power lifters: The effects of age, body mass, competitive standard, and gender. *J Strength Cond Res* 20: 672–681, 2006.
29. Keogh JW, Hume PA, Pearson SN, Mellow PJ. Can absolute and proportional anthropometric characteristics distinguish stronger and weaker powerlifters? *J Strength Cond Res* 23: 2256–2265, 2009.
30. Latella C, van den Hoek D, Teo WP. Factors affecting powerlifting performance: An analysis of age- and weight-based determinants of relative strength. *Int J Perform Anal Sport* 18: 532–544, 2018.
31. Latella C, van den Hoek D, Teo WP. Differences in strength performance between novice and elite athletes: Evidence from powerlifters. *J Strength Cond Res* 33(Suppl 1): S103–S112, 2019.
32. Malcata RM, Hopkins WG. Variability of competitive performance of elite athletes: A systematic review. *Sports Med* 44: 1763–1774, 2014.
33. McGuigan MR, Kane MK. Reliability of performance of elite Olympic weightlifters. *J Strength Cond Res* 18: 650–653, 2004.
34. Miller JD, Ventresca HC, Bracken LE. Rate of performance change in American female weightlifters over ten years of competition. *Int J Exerc Sci* 11: 290–307, 2018.
35. Morton RW, Oikawa SY, Wavell CG, et al. Neither load nor systematic hormones determine resistance training-mediated hypertrophy or strength gains in resistance-trained young men. *J Appl Physiol* 121: 129–138, 2016.
36. Pritchard HJ, Morton RH. Powerlifting: Success and failure at the 2012 Oceania and 2013 classic world championships. *J Aust Strength Cond* 23: 67–70, 2015.
37. Pritchard HJ, Tod DA, Barnes MJ, Keogh JWL, McGuigan M. Tapering practices of New Zealnad's elite raw powerlifters. *J Strength Cond Res* 30: 1796–1804, 2016.
38. Rhodes EC, Martin AD, Taunton JE, et al. Effects of one year of resistance training on the relation between muscular strength and bone density in elderly women. *BJSM* 34: 18–22, 2000.
39. Sander A, Keiner M, Wirth K, Schmidtbleicher D. Influence of a 2-year strength training programme on power performance in elite youth soccer players. *Eur J Sports Sci* 13: 445–451, 2013.
40. Siewe J, Rudat J, Rolinghoff M, et al. Injuries and overuse syndromes in powerlifting. *Int J Sports Med* 32: 703–711, 2011.
41. Smith K, Winegard K, Hicks AL, McCartney N. Two years of resistance training in older men and women: The effects of three years of detraining on the retention of dynamic strength. *Can J Appl Physiol* 28: 462–474, 2003.
42. Stromback E, Aasa U, Gilenstam K, Berglund L. Prevalance and consequences of injuries in powerlifting: A cross-sectional study. *Orthopaedic J Sports Med* 6: 2325967118771016, 2018.
43. Stone MH, Sands WA, Pierce KC, et al. Relationship of maximum strength to weightlifting performance. *Med Sci Sports Exerc* 37: 1037–1043, 2005.
44. Suchomel TJ, Nimphius S, Stone MH. The importance of muscular strength in athletic performance. *Sports Med* 46: 1419–1449, 2016.
45. Swinton PA, Lloyd R, Agouris I, Stewart A. Contemporary training practices in elite British powerlifters: Survey results from an international competition. *J Strength Cond Res* 23: 380–384, 2009.
46. Verkhoshansky Y, Siff M. Specialisation to develop sports mastery. In: *Supertraining* (6th ed.). Rome, Italy: Verkhoshansky SSTM, 2009. pp. 96–97.
47. Vernillo G, Temesi J, Martin M, Millet GY. Mechanisms of fatigue and recovery in upper versus lower limbs in men. *Med Sci Sports Exerc* 50: 334–343, 2018.
48. Yamamoto LM, Lopez RM, Klau JF, et al. The effects of resistance training on endurance distance running performance among highly trained runners: A systematic review. *J Strength Cond Res* 22: 2036–2044, 2008.