Long-term time-course of strength adaptation to minimal dose resistance training: Retrospective longitudinal growth modelling of a large cohort through training records

Received: 27th January 2021

Supplementary materials:

<https://osf.io/jn6ay/>

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ABSTRACT

Public health guidelines for resistance training emphasize a minimal effective dose intending for individuals to engage in these behaviors long-term. However, few studies have adequately examined the longitudinal time-course of strength adaptations to resistance training. The aim of this study was to examine the time-course of strength development from minimal dose resistance training in a large sample through retrospective training records from a private international exercise company. Data was available for analysis from 14,690 participants (60% female; aged 48±11 years) having undergone minimal dose resistance training (1x/week, single sets to momentary failure of six exercises) up to 352 weeks (~6.8 years) in length. Linear-log growth models examined strength development over time allowing random intercepts and slopes by participant. All models demonstrated a robust linear-log relationship with the first derivatives (i.e., changes in strength with time) trending asymptotically such that by ~1-2 years strength had practically reached a 'plateau'. Sex, bodyweight, and age had minimal interaction effects. However, substantial strength gains were apparent; approximately ~30-50% gains over the first year reaching ~50-60% of baseline 6 years later. It is unclear if the 'plateau' can be overcome through alternative approaches, or whether over the long-term strength gains differ. Considering this, our results support public health recommendations for minimal dose resistance training for strength adaptations in adults.

Accepted version: Steele J, Fisher J, Giessing J, Androulakis-Korakakis P, Wolf M, Kroeske B, Reuters R. Long-term time-course of strength adaptation to minimal dose resistance training: Retrospective longitudinal growth modelling of a large cohort through training records. *Res Q Exerc Sport*. 2022. In press

Introduction

Resistance training is a key component of physical activity guidelines worldwide¹, and there have been arguments for the value of a minimal effective dose approach^{2,3}. Indeed, low doses of resistance training (e.g., single sets of a few exercises to target the major muscle groups, performed to a high intensity of effort, performed once a week) can be effective for development of strength⁴⁻⁸.

Strength is associated with function, multi-morbidity, and mortality⁹⁻¹¹ and typically increases in early adult life though declines with age in adults. This decline is ~1% per year¹²⁻¹⁵ though, is non-linear with more gradual decline leading up to approximately 60 years of age, and a more rapid decline afterwards¹⁴⁻¹⁶. Considering the important role of strength, it has been argued that early development of strength capacity is important¹⁷, as is lifetime engagement in resistance training to slow the typical rate of decline with age^{18,19}.

Despite its value there is a paucity of research examining long-term engagement in resistance training. The longest intervention studies typically do not exceed ~2 years and often include relatively small middle to older aged samples ($n = 8$ to 57, aged 50+ years); yet they show large gains in strength (~20-100%) are possible with long-term training²⁰⁻²². However, most of this adaptation occurs within the first year of training^{21,22}. For example, Porter et al.²² showed that, after an initial ~80% increase in strength in the first year, gains plateaued in the second year of training. Further, Hass et al.²³ showed lower relative strength gains (~8-13%) after 13 weeks of resistance training in adults with prior resistance training experience ($n = 42$; 6.2 ± 4.6 years' experience) and who had participated in 1 year of prior minimal dose resistance training.

Longer studies are often cross-sectional and primarily in athletic populations, yet also suggest the presence of an emerging '*plateau*' phenomenon²⁴⁻³¹. Häkkinen et al.²⁴ showed low relative strength gains (2.8%) over 2 years in elite weightlifters ($n = 9$) with at least 7 years prior experience. Baker and Newton²⁵ reported both elite and sub-elite rugby players ($n = 12$) increased strength by ~12.5% over 4 years; yet, when we calculated^a the ratio of gains from the first 2 years of training to the second 2 years (ratio = 1.6:1) it was evident that the magnitude of change decreased over time. Baker^{27,28} also reported little in the way of strength gains after the first 4-5 years in rugby players ($n = 6$ to 11) in follow-ups of 6-10 years. Further, Appleby et al.²⁶ reported negative correlations between baseline strength and gains in strength over a 2-year period in 20 professional rugby union players; this they interpreted as evidence of a '*ceiling*' or '*plateau*' effect (i.e., those who were stronger were assumed to be more trained and have less capacity to gain).

^a Calculated from table 3 in Baker and Newton²⁵ as the mean change in bench press strength from the first two years (1998 to 2000) relative to the mean change from the second two years (2000 to 2002) i.e., $(141-129.6)/(148.1-141) = 1.6$

Recent studies have used larger samples of publicly available data in strength sports²⁹⁻³¹. Miller et al.²⁹ examined 10 years of data from 700+ female weightlifters finding strength did not change meaningfully^b after the first 6 months of competition. Huebner and Perperoglou³⁰ used a cross-sectional approach examining strength from ages 14 to 30 years in a large sample ($n = 3782$) of weightlifters. Strength development was as expected given maturation but after reaching its peak during early to mid-20s essentially 'plateaus' despite continued engagement. Lastly, Latella et al.³¹ examined powerlifters ($n = 1897$) reporting, similarly to Appleby et al.²⁶, that baseline strength was negatively related to gains and suggestive of a 'ceiling' or 'plateau' effect.

Several issues exist in this body of research that affect our understanding of the long-term time-course of strength growth with continued participation in resistance training. Most studies are observations of athletic populations where it is presumed, though perhaps justifiably, that the participants were engaged in resistance training. Though some studies report detail of the programs used based on prior training records, these are typically the kind of interventions employed in such settings and populations (i.e., 'periodised' resistance training). Where direct intervention studies have employed programs more in line with public health guidelines, as noted, these have been in relatively small samples over shorter timeframes. Lastly, no previous studies have employed appropriate within-participant statistical models instead potentially falling prey to the ecological fallacy^{32,33} by focusing cross-sectionally on between-person analyses. Further, the previous interpretations of the association between higher baseline strength levels and smaller gains in strength as supporting a 'ceiling' or 'plateau' effect may be merely regression to the mean and tautological association^{34,35}. A more appropriate approach is the use of hierarchical/mixed growth models whereby timepoints are nested within participants and growth can be modelled incorporating the random variations in both the intercepts and/or slopes between participants³⁶.

We were afforded the opportunity to access a large dataset of individuals having undergone long-term resistance training following a highly standardized protocol in line with current minimal dose recommendations. As such, the aim of this study was to examine the time-course of strength development resulting from continued participation in minimal dose resistance training.

^b Which Miller et al.²⁹ considered changes exceeding a value of $d = 0.3$, where $d = (\Delta / SD_{\text{pooled}})$

Methods

Study design

This study was a retrospective longitudinal growth modelling analysis of strength data from a cohort of members attending training facilities based in the Netherlands operated by a private international exercise company (fit20 International BV, Hattem, Netherlands). Each facility operated by the company uses standardized equipment and training protocols with all members. Training is recorded meticulously during each session on tablet devices (iPad, Apple, Cupertino, CA) and uploaded immediately to a cloud-based database. Participant training records were available to examine from 2009 through to 2017. All data was handled in accordance with the Global Data Protection Regulations (GDPR) meaning appropriate informed consent had been obtained for its sharing and use. No personal data was ever handled by the research team responsible for the analysis and only anonymized data permitting the present analysis was shared. All data used for this analysis is shared with consent and available on the Open Science Framework project page for this study (<https://osf.io/jn6ay/>). Considering the retrospective nature of the study design evaluating existing data, that no identifiable data was involved, all data was handled in accordance with GDPR, and guidance from the Health Research Authority and Research Ethics Committee section 11 of Standard Operating Procedures, *a priori* ethical/IRB approval was not required for this research.

Participants

Data cleaning included filtering to the time interval between the years 2009 and 2017^c, removing impossible values for exercise loads based on the equipment used (see below), and removing those with ages below 18 years as being likely data entry errors. After cleaning training record data was available from 14,690 participants with records ranging up to 352 weeks (~6.8 years) in length. The sample was 60% female and both male and female participants were similarly aged 48±11 years.

^c The year 2009 was the first year that facilities opened and began collecting data in the cloud and as such some retrospectively entered data from paper records prior to this may have errors and so was removed. Further, from 2017 onwards the facilities introduced new sensors technology to their exercise devices to provide additional metrics on workout performance. This resulted in some changes to protocols including loads used by trainees. As such we filtered to this date to ensure that the data set was comparable across time with respect to the protocol employed. We intend at some point in the future to separately analyse the dataset from 2017 onwards using the sensor captured data.

Facilities and Equipment

Training facilities had no music or mirrors, only trainer and participants in the facility, and were air conditioned at a constant ~17-18°C. All facilities were equipped with Nautilus One (Core Health and Fitness, Vancouver, WA) resistance machines. This included leg press, chest press, pulldown, abdominal flexion, back extension, and both seated hip adduction and abduction machines. For the current analysis, we present the leg press, chest press, and pulldown.

Training Protocols

As clients of the training facilities, each participant underwent the standardized training protocol at a planned frequency of 1x/week. Sessions were always completed under supervision from a trainer, with a trainer to trainee ratio of 1-to-1 or 1-to-2. Trainees typically^d performed 6 exercises including chest press, pulldown, leg press, abdominal flexion, back extension, and either hip adduction or abduction (alternated each session). Exercises were typically performed in that order, except where two participants trained at the same time in which case each sequential pair was alternated between participants (i.e., first one performed the chest press and the other the pulldown, then they swapped). In some facilities there were also roman chair and rotary torso machines which were used intermittently. Each exercise was completed for a single set using a load selected by the trainer that was intended to allow participants to perform between four to six repetitions before reaching momentary failure as defined in Steele et al.⁴. Where the initial loads selected are either too heavy or too light, this was adjusted in the subsequent session and the appropriate load is typically achieved within ~2 sessions. Repetitions were performed through a full range of motion, yet which avoided unloading at the extremities (i.e., avoiding full lockout on pushing movements, and avoiding unloading the weight at the bottom of all exercises) using a repetition duration of 10 seconds concentric and 10 seconds eccentric. Thus, time under load was intended to fall within a range of ~80-120 seconds. Participants received feedback from the trainer on their repetition duration (i.e., speed up/slow down) who monitored this with a stopwatch and encouraged strict form, continuous breathing, achieving the desired range of motion, and maintaining constant loading throughout. For the latter they coached participants to focus on smooth changes of direction at the turnarounds for each repetition (i.e., upon reaching either end of the range of motion and changing direction of movement from concentric to eccentric and vice versa), avoiding unloading and resting at the end of the eccentric, and avoiding excessive momentum at the beginning of the concentric. Participants progressed from exercise to exercise quickly as soon as they felt ready to do so, and typically

^d Where exercises were missed in any given session this was usually due to injury preventing a particular exercise being completed.

with ~20 seconds rest between exercises. Thus, total session time was always <20 minutes. Participants continued each set of each exercise to momentary failure and when they exceeded the target repetition/time under load range training loads were progressed from between ~1-10%. Load progression within this range was based on the machine being used (i.e., the increments possible), the current training load, and how far they exceeded the repetition/time under load range^e. In addition, the supervisor appraised whether they were able to maintain continuous breathing, appropriate exercise form/posture, and the prescribed repetition duration with their current load and performance.

Strength Outcomes

Due to the implementation of the standardized training protocols over time described above and given the relationship between maximal strength and the load with which one can perform a fixed number or range of repetitions when performed to momentary failure³⁷, we were able to operationalize training loads used during exercise sessions as our strength outcome in the present analysis. Given their multi-joint nature and that we considered that they would likely be reasonable reflective of generalizable strength gain, the loads for leg press, chest press, and pulldown exercises in each training session were examined. Given that participants trained using the same repetition duration and time under load/repetition range to momentary failure for each session, and that once participants exceeded this range they had their load progressed systematically for the next session, we were able to consider load progression as indicative of increased strength performance.

Statistical Analysis

Analysis for this study was not pre-registered and was treated as exploratory. Thus, inferential statistics from the analysis of the dataset generated from our participants should be treated as highly unstable local descriptions of the relations between model assumptions and data to acknowledge the inherent uncertainty in drawing generalised inferences from single samples³⁸. However, considering the sample size for this present study we consider our results well generalisable to the sampled population and training approach utilised i.e., exercise facility members participating in minimal dose resistance training. Further, we also fit similar models as described below to other publicly available datasets^f to explore their

^e When exceeding the upper range of the target time under load by ≤ 10 seconds the load was increased by the smallest increment on the resistance machine which was 2.5 kg, and if >10 seconds it was increased by 5 kg.

^f The two additional datasets included the Open Powerlifting dataset (available from <https://openpowerlifting.gitlab.io/opl-csv/introduction.html>) and a survey of users of the Reddit forum r/weightroom (available from

generalisability which are described briefly in the results and discussion. For all analyses we opted to avoid dichotomising the existence of effects and therefore did not employ traditional null hypothesis significance testing, which has been extensively critiqued^{39,40}. Instead, though we present p values for model summaries, we consider the implications of all results compatible with these data, from the lower limit to the upper limit of interval estimates, with the greatest interpretive emphasis placed on the point estimates. Further, we focus primarily on qualitative description of our results based on visualisation of the data and models. All analysis was conducted in R (v4.1.2; R Core Team, <https://www.r-project.org/>) and all data and code utilised is presented in the supplementary materials (<https://osf.io/jn6ay/>).

Mixed effects growth modelling was performed where strength for each exercise (i.e., loads used for leg press, chest press, and pulldown) were the dependent variables. Random intercepts and slopes for time for individual participants were included. Time was defined continuously as the natural logarithmic transformation of 'time' in weeks based on the conversion of session dates from the first session date. Time was transformed on the natural logarithm given the non-linear trajectories of strength that were apparent in the raw data, and further that a linear-log growth model had a priori plausibility given it would be unexpected for strength to continue to increase over the time period explored to the same magnitude. Despite this, we initially visually explored several models where time was treated linearly, or as a second order polynomial, on both raw and logarithmic transformations. A random sample of 20 participants were drawn and leg press strength explored. These models were fitted on this sample and the respective model predicted values were plotted and compared with the raw values. The difference in fit when inspected visually (see <https://osf.io/cpd9y/>), and the respective conditional R^2 values (see <https://osf.io/rpjuv/>), was negligible between the models and so we opted to utilise the linear-log model formulation to facilitate easier interpretation of model coefficients. Model formulation was thus:

Level 1

$$Y_{ij} = \beta_{0j} + \beta_{1j} \log(\text{time})_{ij} + \epsilon_{ij}$$

Level 2

$$\beta_{0j} = \gamma_{00} + U_{0j}$$

$$\beta_{1j} = \gamma_{10} + U_{1j}$$

<https://docs.google.com/spreadsheets/u/0/d/1w8FnxOtDissaB89AsdqXrVvydv-fF2mhha3vDtxWVCY/htmlview>). Both datasets used have also been uploaded to the project page on the Open Science Framework (see <https://osf.io/jn6ay/>).

We also examined separate^g models of the interaction effects of age (years) and body weight (kg) as continuous variables and sex thus formulating level 2 in these models as:

Level 2 (age)

$$\beta_{0j} = \gamma_{00} + \gamma_{01}age_j + U_{0j}$$

$$\beta_{1j} = \gamma_{10} + \gamma_{11}age_j + U_{1j}$$

Level 2 (sex)

$$\beta_{0j} = \gamma_{00} + \gamma_{01}sex_j + U_{0j}$$

$$\beta_{1j} = \gamma_{10} + \gamma_{11}sex_j + U_{1j}$$

Level 2 (bodyweight)

$$\beta_{0j} = \gamma_{00} + \gamma_{01}bodyweight_j + U_{0j}$$

$$\beta_{1j} = \gamma_{10} + bodyweight + U_{1j}$$

All models were fit using the 'lme4' package⁴¹ with Restricted Maximum Likelihood Estimation and Nelder-Mead optimisation⁴². Model summary tables were produced using the 'sjPlot' package⁴³. Standardised beta coefficients using Gelman's⁴⁴ standardisation by two standard deviations were also produced and included in model summary tables to allow for comparison across models and to any future longitudinal growth models for strength from different datasets. Profile likelihoods were also used to compute confidence intervals for the random effects correlations (i.e., between random intercept and slope). Model diagnostics were inspected on a random sample of 1000 participants to better facilitate visualisation (i.e., avoid overplotting) using the 'performance' package⁴⁵.

Data visualisation for the main model included calculation of model predicted values and 95% prediction intervals using the 'ggeffects' package⁴⁶ to communicate the model uncertainty. Prediction intervals accounted for residual (observation-level) variance, uncertainty in fixed coefficients, and uncertainty in the variance parameters for any grouping factors. We also plotted the first derivative (i.e., where $y_{strength} = \beta \log(time)$, $\frac{d_{strength}}{d_{time}} = \frac{\beta}{time}$) of our main models transformed to a standardised effect (d) where the denominator was the intercept standard deviation (i.e., $d \cdot week^{-1} = \frac{\left(\frac{d_{strength}}{d_{time}}\right)}{U_{ij}}$) to enable better visualisation of the asymptotic trend and for qualitative interpretation of when a 'plateau' practically speaking emerged. We also show these derivatives and the summed standardised effect over the first 12 weeks of training to provide some comparison of effects with the typical resistance training intervention study length. Further, we fit a degree one spline with a single knot point of

^g These were modelled separately as we did not have complete case-wise data for all covariates.

unknown location to each time series of a random sample of 1000 participants^h with ≥ 100 sessions where the location of the knot point was unknown using the 'SiZer' packages piecewise.linear function⁴⁷. The purpose of this was to identify at what time change points (i.e., where the initial slope of strength growth for individuals changed) occurred which were then visualised as distributions using density plots with modes and quantile intervals using the 'ggdist' package⁴⁸. Visualisation for the interaction models was done with marginal effects for interactions presented across a range of age values (30, 50, and 70 years), bodyweight values (60 kg, 80 kg, and 100kg), and for sex as separate curves (i.e., male and female). Interaction plots were presented as the model predicted values and 95% confidence intervals. All plots are presented on both the raw untransformed time scale, and on the common logarithmic scale. Additionally, for the main models, and both the bodyweight and sex interactions, the fitted values were rescaled as a percentage value normalised to the fitted value at time 1 and each individual curve re-plotted for visual comparison of strength change magnitudes. All figures show the models presented in lme4 (Wilkinson) syntax.

Lastly, given the longitudinal model employed we attempted to rule out the possible explanation that, given a larger proportion of participants had data for shorter time periods (see supplementary materials <https://osf.io/gezhw/>), weaker individuals dropping out may account for any apparent plateau in strength with time (i.e., survivorship bias). We refit the model above limiting the sample to only those participants with >100 weeks of observation (i.e., at least ~ 2 years of data) and additionally explored whether there was any correlation between the random intercepts by participants from the main model and the number of sessions for which they had data available.

Results

All model diagnostic plots are available in the online supplementary materials (see "Model Diagnostic Plots"; <https://osf.io/jn6ay/>). Briefly, all relevant model assumptions were met except for some deviation from normality of distribution in the residuals at the tails. However, we were unconcerned with this given that both linear regression models with large samples^{47,48}, and mixed models^{49,50} are typically robust to deviation from normality assumptions, particularly where simple growth models with a single random intercept and slope are employed such as we have used here⁵¹.

Main Models

Across all exercises similar patterns of strength growth were observed (figure 1). Our models demonstrated a robust linear-log relationship between strength and time indicating

^h Due to the computational time required to fit the models a reasonably large, yet manageable random sample was used.

that as time progressed the magnitude of strength changes diminished (right panels in figure 1). Examining the fitted models on the untransformed time scale (left panels in figure 1), and the first derivatives (figure 2) clearly indicates that rapid strength adaptation occurs initially (for the first 12 weeks $d = 0.86, 0.58$, and 0.77 for leg press, chest press, and pulldown respectively) and continues up to the first ~1-2 years of resistance training though trends asymptotically before reaching a 'plateau' practically speaking ($d.week^{-1} \approx 0$). However, the changepoint estimations suggested that the slope of initial growth may begin to change somewhat earlier on average (~26 to 31 weeks) though with considerably variability between individuals (figure 3). Standardised beta coefficients for $\log(\text{time})$ indicated that strength progression was large across exercises and occurred most rapidly for the leg press, followed by pulldown and then chest press. Rescaling strength as percentage of baseline showed approximately ~30-50% gains over the first year, yet 6 years later gains had only reached ~50-60% of baseline (figure 4). Small negative correlations between random effects were observed (leg press $\rho = -0.34$ [95%CI -0.36 to -0.33], chest press $\rho = -0.19$ [95%CI -0.21 to -0.17], pulldown $\rho = -0.33$ [95%CI -0.35 to -0.31]) suggesting stronger individuals at baseline had slightly lesser gains in strength over time. Formal model summaries for each exercise are presented in table 1.

All main models on both untransformed (left), and common logarithmic (right) x axes

Figure 1. Main model fitted values (solid lines) and 95% prediction intervals (grey ribbons).

First derivatives from all main models marginal effects

Figure 2. First derivatives from main models.

Estimation of Changepoints

Changepoints estimated from single knot spline model with unknown knot location
 A random sample of 1000 participants with at least ~2 years data were used
 Point is the mode of the density function and the intervals are the 95% quantile interval

Figure 3. Density plots for changepoint estimation models with mode and 95% quantile intervals.

All main models with y axes rescaled (% baseline) on both untransformed (left), and common logarithmic (right) x axes

Figure 4. Main model fitted values rescaled as percentage of baseline strength values.

Table 1 Main model summaries

Predictors	Leg Press Exercise Load (kg)						Chest Press Exercise Load (kg)						Pulldown Exercise Load (kg)					
	Estimates	std. Beta	CI	standardized CI	p	std. p	Estimates	std. Beta	CI	standardized CI	p	std. p	Estimates	std. Beta	CI	standardized CI	p	std. p
(Intercept)	84.66	-	84.17 – 85.14	-0.71 – -	<0.001	<0.001	29.44	-	29.26 – 29.63	-0.46 – -	<0.001	<0.001	36.53	-	36.32 – 36.75	-0.62 – -	<0.001	<0.001
		0.70		0.68				0.45		0.43				0.60		0.59		
time [log]	9.85	1.48	9.70 – 10.00	1.45 – 1.50	<0.001	<0.001	2.61	0.94	2.56 – 2.67	0.91 – 0.96	<0.001	<0.001	4.01	1.28	3.94 – 4.07	1.25 – 1.30	<0.001	<0.001
Random Effects (Variances)																		
σ²	101.71						12.48						20.32					
τ₀₀	813.07	participant					123.98	participant					165.33	participant				
τ₁₁	64.07	participant.log(time)					8.15	participant.log(time)					11.53	participant.log(time)				
ρ₀₁	-0.34	participant					-0.19	participant					-0.33	participant				
ICC	0.92						0.94						0.91					
N	14187	participant					14571	participant					14279	participant				
Observations	523429						555483						549409					
Marginal R² / Conditional R²	0.109 / 0.925						0.049 / 0.941						0.092 / 0.923					

Sex Interaction

Sex impacted model intercepts across all exercises with males having greater strength at baseline and continuing across time (figure 5). Standardised intercepts showed a large effect of sex, and standardised beta coefficients most strongly supported an interaction effect with $\log(\text{time})$ for chest press and pulldown where males had more steeper slopes indicating faster strength progression over time. Leg press showed similar results albeit more attenuated with more similarity in slopes over time. Standardised beta coefficients for interaction effects were however relatively smaller than those for intercepts. When rescaled as a percentage of baseline strength there were only small differences between males and females (figure 6). Formal model summaries for each exercise are presented in table 2.

Figure 5. Sex interaction model fitted values and 95% compatibility (confidence) intervals

All sex interaction models with y axes rescaled (% baseline) on both untransformed (left), and common logarithmic (right) x axes

Figure 6. Sex interaction model fitted values rescaled as percentage of baseline strength values and 95% compatibility (confidence) intervals

Table 2. Sex interaction model summaries

Predictors	Leg Press Exercise Load (kg)						Chest Press Exercise Load (kg)						Pulldown Exercise Load (kg)					
	Estimates	std. Beta	CI	standardized CI	p	std. p	Estimates	std. Beta	CI	standardized CI	p	std. p	Estimates	std. Beta	CI	standardized CI	p	std. p
(Intercept)	77.37	-	76.33 – 78.40	-1.05 – -	<0.001	<0.001	25.08	-	24.73 – 25.44	-0.88 – -	<0.001	<0.001	32.64	-	32.21 – 33.08	-1.00 – -	<0.001	<0.001
		1.02		1.00				0.85		0.83				0.97		0.95		
time [log]	8.69	1.34	8.37 – 9.01	1.28 – 1.40	<0.001	<0.001	1.72	0.65	1.61 – 1.83	0.60 – 0.70	<0.001	<0.001	2.92	0.98	2.79 – 3.05	0.92 – 1.03	<0.001	<0.001
Sex [male]	25.82	0.82	24.18 – 27.45	0.78 – 0.86	<0.001	<0.001	14.03	1.14	13.47 – 14.59	1.10 – 1.17	<0.001	<0.001	13.25	1.00	12.56 – 13.94	0.96 – 1.04	<0.001	<0.001
time [log] * Sex [male]	1.52	0.10	1.01 – 2.02	0.00 – 0.19	<0.001	0.045	1.36	0.40	1.19 – 1.54	0.32 – 0.48	<0.001	<0.001	1.62	0.40	1.42 – 1.83	0.32 – 0.48	<0.001	<0.001
Random Effects (Variances)																		
σ²	122.73						13.98						23.63					
τ₀₀	807.38 participant						99.44 participant						144.72 participant					
τ₁₁	66.92 participant.log(time)						7.94 participant.log(time)						11.04 participant.log(time)					
ρ₀₁	-0.49 participant						-0.49 participant						-0.58 participant					
ICC	0.89						0.89						0.86					
N	5121 participant						5267 participant						5182 participant					
Observations	257658						277347						273058					
Marginal R² / Conditional R²	0.270 / 0.917						0.441 / 0.940						0.420 / 0.917					

Age Interaction

Age impacted model intercepts across all exercises with reduced strength with increasing age at baseline and which continued across time (figure 7). Standardised intercepts showed that the effect of age was relatively small to moderate. Standardised beta coefficients most strongly supported an interaction effect with log(time) for leg press where younger participants had more steeper slopes indicating faster strength progression over time. Chest press and pulldown interaction effects were far weaker and seemed negligible. Formal model summaries for each exercise are presented in table 3.

All age interaction models on both untransformed (left), and common logarithmic (right) x axes

Figure 7. Age interaction model fitted values and 95% compatibility (confidence) intervals

Table 3. Age interaction model summaries

Predictors	Leg Press Exercise Load (kg)						Chest Press Exercise Load (kg)						Pulldown Exercise Load (kg)					
	Estimates	std. Beta	CI	standardized CI	p	std. p	Estimates	std. Beta	CI	standardized CI	p	std. p	Estimates	std. Beta	CI	standardized CI	p	std. p
(Intercept)	106.60	-	104.71 – 108.48	-0.72 – -	<0.001	<0.001	36.38	-	35.66 – 37.10	-0.47 – -	<0.001	<0.001	44.65	-	43.79 – 45.50	-0.62 – -	<0.001	<0.001
		0.71		0.70				0.46		0.44				0.61		0.60		
time [log]	12.30	1.48	11.71 – 12.89	1.45 – 1.50	<0.001	<0.001	2.85	0.94	2.64 – 3.05	0.91 – 0.96	<0.001	<0.001	4.56	1.28	4.31 – 4.81	1.25 – 1.30	<0.001	<0.001
age	-0.46	-	-0.49 – -0.42	-0.17 – -	<0.001	<0.001	-0.14	-	-0.16 – -0.13	-0.13 – -	<0.001	<0.001	-0.17	-	-0.19 – -0.15	-0.13 – -	<0.001	<0.001
		0.16		0.14				0.12		0.11				0.12		0.10		
time [log] * age	-0.05	-	-0.06 – -0.04	-0.13 – -	<0.001	<0.001	-0.00	-	-0.01 – -0.00	-0.04 – -	0.027	0.048	-0.01	-	-0.02 – -0.01	-0.09 – -	<0.001	<0.001
		0.10		0.08				0.02		0.00				0.07		0.04		
Random Effects (Variances)																		
σ ²	101.71						12.48						20.31					
τ ₀₀	780.21	participant					120.39	participant					161.26	participant				
τ ₁₁	63.51	participant.log(time)					8.14	participant.log(time)					11.52	participant.log(time)				
ρ ₀₁	-0.36	participant					-0.20	participant					-0.34	participant				
ICC	0.91						0.94						0.91					
N	14187	participant					14571	participant					14279	participant				
Observations	523429						555483						549409					
Marginal R ² /	0.148 / 0.925						0.066 / 0.941						0.113 / 0.923					
Conditional R ²																		

Bodyweight Interaction

Bodyweight impacted model intercepts across all exercises with heavier individuals having greater strength at baseline and continuing across time (figure 8). Standardised intercepts showed a moderate effect of bodyweight, and standardised beta coefficients most strongly supported an interaction effect with log(time) for chest press and pulldown where heavier individuals had more steeper slopes indicating faster strength progression over time. Leg press showed similar results albeit more attenuated with more similarity in slopes over time. Standardised beta coefficients for interaction effects were however relatively smaller than those for intercepts. When rescaled as a percentage of baseline strength there were only small differences with respect to bodyweight (figure 9). Formal model summaries for each exercise are presented in table 4.

Figure 8. Sex interaction model fitted values and 95% compatibility (confidence) intervals

All bodyweight interaction models with y axes rescaled (% baseline) on both untransformed (left), and common logarithmic (right)

Figure 9. Sex interaction model fitted values rescaled as percentage of baseline strength values and 95% compatibility (confidence) intervals

Table 4. Bodyweight interaction model summaries

Predictors	Leg Press Exercise Load (kg)						Chest Press Exercise Load (kg)						Pulldown Exercise Load (kg)					
	Estimates	std. Beta	CI	standardized CI	p	std. p	Estimates	std. Beta	CI	standardized CI	p	std. p	Estimates	std. Beta	CI	standardized CI	p	std. p
(Intercept)	38.31	-0.73	34.77 – 41.84	-0.75 – - 0.71	<0.001	<0.001	10.95	-0.45	9.63 – 12.27	-0.47 – - 0.43	<0.001	<0.001	16.52	-0.61	14.88 – 18.16	-0.63 – - 0.59	<0.001	<0.001
time [log]	7.62	1.53	6.46 – 8.78	1.48 – 1.57	<0.001	<0.001	0.33	0.98	-0.08 – 0.74	0.95 – 1.02	0.115	<0.001	1.26	1.33	0.75 – 1.77	1.29 – 1.38	<0.001	<0.001
bodyweight	0.62	0.32	0.57 – 0.66	0.30 – 0.34	<0.001	<0.001	0.23	0.31	0.21 – 0.24	0.29 – 0.33	<0.001	<0.001	0.25	0.30	0.23 – 0.27	0.28 – 0.32	<0.001	<0.001
time [log] * bodyweight	0.03	0.08	0.01 – 0.04	0.03 – 0.12	<0.001	<0.001	0.03	0.17	0.02 – 0.03	0.14 – 0.21	<0.001	<0.001	0.04	0.19	0.03 – 0.04	0.15 – 0.23	<0.001	<0.001
Random Effects (Variances)																		
σ^2	123.88						14.56						24.36					
τ_{00}	787.50	participant					114.30	participant					169.96	participant				
τ_{11}	69.07	participant.log(time)					8.68	participant.log(time)					13.20	participant.log(time)				
ρ_{01}	-0.48	participant					-0.29	participant					-0.48	participant				
ICC	0.88						0.92						0.89					
N	6208	participant					6357	participant					6160	participant				
Observations	217030						229499						226694					
Marginal R ² / Conditional R ²	0.212 / 0.906						0.189 / 0.934						0.234 / 0.912					

Survivorship Bias?

When models were refit on only those participants with ≥ 100 sessions model coefficients did not differ drastically from the main models except for attenuated standardised estimates (see supplementary materials <https://osf.io/y3bd4/>). Model fitted values qualitatively showed the same shape to the time-series (see supplementary materials <https://osf.io/kha6b/>) which suggested that strength plateaus were not occurring merely as an artefact of survivorship bias. Lastly, when examining the relationships between random effects and length of time for which participants had observations, though there were slight tendencies towards higher random intercepts when over the untransformed timescale, for $\log(\text{time})$ there were essentially no relationships for either intercepts or slopes (see supplementary materials <https://osf.io/tzwja/>). Thus, we were confident that our models appropriately reflected the effects of participation in minimal dose resistance training over time absent survivorship bias.

Generalisability of Linear-Log Strength Growth

To explore the generalisability of the functional forms of the models employed in the present study (particularly given the nature of the training intervention prescribed) we applied the same longitudinal growth model as used for the main models described above (i.e., random intercepts by participant, and random slopes for time on the natural logarithmic scale) to a random sample ($n = 10,000$) powerlifters from the Open Powerlifting Dataset, and also fit a simple linear model (i.e., without random effects) for $\log(\text{time})$ to a cross-sectional dataset of people engaged recreationally in resistance training from the r/weightroom Reddit forum ($n = 1069$). We limited our exploratory analyses to examining the effects of $\log(\text{time})$ on the total (kg) of squat, bench press, and deadlift (i.e., meet performance for the powerlifters, and self-reported one-repetition maximum for the recreational lifters). Both datasets similarly were well fit by the linear-log models (see folder “Additional models with other datasets” in the supplementary materials for model summary tables and figures; <https://osf.io/jn6ay/>).

Discussion

The results of this study demonstrate that, despite substantial initial gains in strength during the first ~1-2 years of participation in minimal dose resistance training, a ‘plateau’ in growth occurs with gains trending asymptotically towards zero over continued participation. Changepoint estimation suggested the change from initial rapid strength growth may begin earlier on average (~26 to 31 weeks) with considerable between participant variation, though this model is not necessarily as physiologically plausible as our main model. The main linear-log model was however a strong fit for this relationship which has intuitive plausibility over the timeframe explored (~6.8 years) where gains and then maintenance might be expected. Stronger individuals at baseline had slightly lesser strength gains over time when considering

the correlations between random effects which were however stronger ($p = -0.34$ to -0.19) than those previously found in studies not employing mixed effects growth models for baseline strength and changes in strength ($r = -0.073$ to 0.027)³¹. Unsurprisingly, sex and age impacted model intercepts (i.e., baseline strength) with males and both heavier and younger adults exhibiting greater strength than their female, lighter, and older comparators. However, the interactions of sex, bodyweight, and age with time was minimal, with largely similar slopes (i.e., growth curves over time) and 'plateaus'. Using appropriate longitudinal growth modelling, this study supports previous suggestions of the emergence of a '*plateau*' or '*ceiling*' phenomena for strength resulting from resistance training.

Why a 'plateau' in strength after ~1-2 years of participation in minimal dose resistance training specifically occurs is worth considering; and, whether this represents a general phenomenon or one specific to this context. Some might consider the emergence of a 'plateau' a result of unvaried stimuli in the standardised protocol employed, or that over time greater volumes of training are required to ensure continued adaptation. However, the hypothesis that variation in the specific variables that comprise a resistance training bout are required for *continued* strength adaptation in the long-term lacks a clear physiological rationale and empirical support^{54,55}. Meta-analyses on the effects of volume upon strength also suggest only trivially greater effects with moderate to higher volumes over the short term; further, they highlight that there is little data to enable identification of interaction effects with training experience⁶. More directly examining this, Hass et al.²³ have shown that increasing volume after an initial year of minimal dose resistance training in previously resistance trained adults does not result in any greater adaptations than continuation of the minimal dose protocol. Indeed, both continuation of the minimal dose and increasing the dose resulted in relatively minimal adaptations.

Of course, given the specificity of strength adaptation is dependent upon the way the variable is operationalised for measurement⁵⁶, it may be possible to elicit continued improvement even after previous resistance training experience with specific training. By way of comparison to our existing results, and to explore their generalisability, we fit an equivalent longitudinal growth model to a random sample of powerlifters from the Open Powerlifting Dataset⁹. It would seem a reasonable assumption that most who begin to engage in powerlifting competition have been previously exposed to resistance training. Yet, the choice to engage in powerlifting competition likely means training shifts specifically towards optimisation of strength as operationalised in that context (i.e., 1RM for squat, bench press, and deadlift). Further, powerlifters overwhelmingly employ periodisation in their training programs^{57,58}. In this exploratory powerlifting model relative gains were

⁹ Note, a full analysis of this dataset is currently underway and will be presented in a separate forthcoming manuscript.

substantially smaller (~12.5%) compared with our present results (~50-60%) over the same ~6-year period. This of course would be expected given the assumption powerlifters were probably more experienced in resistance training upon beginning competition. Additionally, they were able to improve their total (kg) supporting the notion of some additional specific performance gains that might result from a shift towards specific powerlifting training. However, despite this, we still observe the emergence of a 'plateau' after ~1 year of competition (see <https://osf.io/dfqug/>). While continued strength gains may be possible, these results question the degree to which the typical application of variation through periodisation by powerlifters can enable continued strength adaptation with time in the long-term. Thus, although some evidence suggests in the short-term (6 to 36 weeks) periodization might have a small enhancing effect on strength gains⁷, given sufficient time (≥ 1 year) practically speaking 'plateaus' may be unavoidable irrespective of training approach. Collectively this evidence lends support to relatively early 'plateaus' in strength with resistance training as being a robust phenomenon.

The observation that strength appears to be well described with respect to time by a linear-log model resulting in 'plateaus' emerging over roughly similar timeframes, even across different populations and training approaches, presents interesting practical implications. In support of recommendations from a public health perspective¹⁻³, relatively simple minimal dose resistance training approaches can produce substantial strength gains which can be maintained over the long-term. Further, minimal dose approaches may offer utility to previously trained populations who may still produce small gains from their use⁵⁹, or at the least likely maintain strength already attained. Lastly, the present findings have particularly valuable implications for older populations considering the ~1% decline in strength per year that occurs with ageing¹²⁻¹⁶. Over the ~6-year period of observation for this study, absent resistance training the older adults in the sample would have lost an expected ~6% of strength. However, we found that strength gains were still substantial, and maintained over this period even in these older participants. This lends support to the notion of '*bending the aging curve*' as proposed by Signorile⁶⁰.

The strengths and limitations of the present study should be considered. Of course, a limitation is its observational nature limiting causal claims; however, considering the well evidenced time course of strength curves in adults with maturation and ageing absent resistance training, and the exclusion of survivorship bias explanations, we feel confident the growth curves presented are reflective of causal effects with time for minimal dose resistance training. A benefit to the utilization of observational data is that we were able to examine a larger sample than is feasible in experimental research. Indeed, to our knowledge this study is the largest thus far to investigate long-term strength adaptations to resistance training. Further, we employed more appropriate statistical analysis for longitudinal growth

modelling. Despite this, relative to the typical lifespan of humans, the timeframe described by our dataset is still relatively short. Given the known decline of strength with ageing¹²⁻¹⁶, it may be that over sufficient time a linear-log model is no longer a good description of the data generating process. Indeed, astute readers may have noticed the references throughout to 'plateau' which was because a true plateau is never reached by a linear-log model (even if practically speaking it could be considered to be). Future work that is able to model strength over the life course in those continuously engaged in resistance training may best describe this process with a second order polynomial model that incorporates a true plateau and also the gradual decline with strength resultant from ageing. Both a strength and limitation to this study is the examination of a very specific standardized minimal dose resistance training approach. Such standardization enabled operationalization of training loads as strength. However, the lack of variation in resistance training approaches means that we can only draw indirect comparisons to other approaches regarding the functional form of time in strength development (as we have done so with the Open Powerlifting and r/weightroom dataset above). It is not directly clear whether *changing* the specific resistance training performed (i.e., loads, volumes, exercise selections etc.), or indeed other factors such as anthropometric or dietary changes, might enable further strength adaptation after the emergence of the 'plateau' occurs. Thus, future investigators should consider the availability of datasets where alternative resistance training approaches have been employed, or where anthropometric or dietary data over time have also been captured. Indeed, where within-bout training variables have been recorded this might enable their inclusion in modelling to explore their impact upon the shape of strength growth curves with time. In addition, the minimal dose resistance training examined in this study was conducted under a high supervision ratio (1-to-1 or 2-to-1 trainer to trainee). Thus, while the results inform us regarding longitudinal strength growth, further research should explore whether similar adaptation occurs under unsupervised conditions more akin to that which the general public would be likely to engage in. There is some indication of similar linear-log growth curves, and similar magnitude isometric strength adaptation from unsupervised machine-based resistance training in a large sample of adults aged over 55 years (see figure 1 in reference ⁶¹ and also a recent meta-analysis suggests only a small benefit to supervision⁶²). Further, there may be some concern regarding the use of load progression as our operationalization of strength adaptation and that this was to some extent dictated by trainers who might be motivated to progress load and thus overestimate change. Given the nature of the dataset however this was a necessity (i.e., we did not have typical direct measures of strength such as repetition maximum tests or dynamometry). Further, trainers followed strict progression rules as dictated by the protocols employed across facilities. Thus, load progression was primarily a result of performance by individual participants and

occurred when they exceeded the repetition/time under load thresholds whilst maintaining good form (admittedly appraised by the trainer). Increases in repetitions to failure at a given load (i.e., absolute endurance), or increases in loads for submaximal load repetition maximum testing (which is essentially what our operationalization for strength was) are related to changes in maximal strength measures such as one repetition maximum tests and thus could be considered adequate proxies³⁷. Although, arguably most studies exploring this relationship have used repetition durations considerably shorter than those employed in the protocol for this study. However, such slow “grinding” repetitions, at least on the final repetition to momentary failure, could be argued to have some face validity to the typically slow velocities achieved during a one-repetition maximum. Also, the similarity of effect sizes in the first 12 weeks to that seen in recent meta-analysis of resistance training in randomized controlled trials ($d = 0.88$ [95%CI 0.80 to 0.98])⁶³, similarity of growth curves seen for the Open Powerlifting and r/weightroom datasets where one-repetition maximum was the strength operationalization, and indeed in the isometric strength data noted above⁶¹ suggested that our operationalization is likely a valid generalisable indicator of strength growth.

Conclusion

To conclude, substantial strength gains are possible with the use of a minimal dose resistance training approach and well described by a linear-log model. Though, strength begins to plateau after ~1-2 years of training with little impact from sex, bodyweight, or age on the emergence of this ‘plateau’. These findings also seem generalisable across populations and training approaches. Considering this, our results support the use of minimal dose resistance training approaches, particularly from a public health perspective, to induce and maintain strength adaptations in adults.

Acknowledgement

The authors would like to thank Andrew Vigotsky for his insights regarding the statistical modelling approach taken in this study.

Funding information

No funding was received in support of this research.

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/jn6ay/>

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