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

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ABSTRACT

Introduction: Public health guidelines for resistance training typically emphasize a minimal effective dose approach. The intention for such guidelines is that individuals engage in these behaviors over the long-term. However, relatively few studies have examined the longitudinal time-course of strength adaptations to resistance training and those which have typically utilize small samples and/or athletic populations. Further, no studies have employed approaches to incorporate participant level random factors into modelling. Thus, the aim of this study was to examine the time-course of strength development resulting from continued participation in minimal dose resistance training in a large sample through retrospective training records. ***Methods:*** Data was available for analysis from 14,690 participants who had undergone minimal dose resistance training (1x/week, single sets to momentary failure of six exercises) with records ranging up to 352 weeks (~6.8 years) in length. Linear-log growth models examining the development of strength over time were fit allowing random intercepts and slopes by participant. In addition, the interaction of sex and age were examined as fixed effects. ***Results:*** All models demonstrated a robust linear-log

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relationship which on the untransformed time scale clearly demonstrated the presence of a plateau in strength development around ~1 year into training after which strength was essentially maintained with minimal growth. Sex and age had minimal interaction effects. ***Conclusions:*** Substantial strength gains are possible with the use of a minimal dose resistance training approach. Though, these begin to plateau after ~1 year of training with little impact from sex or age on the emergence of this plateau. It is unclear if this plateau can be overcome through alternative approaches. Considering this, our results support public health recommendations for minimal dose resistance training to induce and maintain strength adaptations in adults.

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Introduction

Resistance training is a key component of physical activity guidelines worldwide (Bull et al., 2020), and there have been arguments for the value of a minimal effective dose approach (Steele et al., 2017; Fisher et al., 2017). Indeed, low doses of resistance training comprising single sets of a few exercises to target the major muscle groups, performed to a high intensity of effort (i.e. to, or near to, momentary failure; Steele et al., 2017) performed once a week, can be effective for development of strength (Schoenfeld et al., 2017; Ralston et al., 2017; Grgic et al., 2018; Williams et al., 2017).

Strength is associated with function, multi-morbidity, and mortality (Garciá-Hermoso et al., 2018; Dodds et al., 2020; Wang et al., 2020) and typically increases in early adult life though declines with age in adults. This decline is ~1% per year (Rantanen et al., 1998; Frontera et al., 2000; Dodds et al., 2014) though, is non-linear with more gradual decline leading up to approximately 60 years of age, and a more rapid decline afterwards (Nahhas et al., 2010; Dodds et al., 2014; Kemmler et al., 2018). Considering the important role of strength, it has been argued that early development of strength capacity is important (Buckner et al., 2017), as is lifetime engagement in resistance training to slow the typical rate of decline with age (Aagard et al., 2007; Unhjem et al., 2016).

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 training (Smith et al., 2003; McCartney et al., 1996; Porter et al., 2002). However, most of this adaptation occurs within the first year of training (McCartney et al., 1996; Porter et al., 2002). For example, Porter et al. (2002) 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., (2000) 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* phenomenon (Häkkinen et al., 1988; Baker and Newton, 2006; Appleby et al., 2012; Baker, 2008; Baker et al., 2013; Miller et al., 2018; Huebner and Perperoglou, 2019; Latella et al., 2020). Häkkinen et al. (1988) showed low relative strength gains (2.8%) over 2 years in elite weightlifters (*n* = 9) with at least 7 years prior experience. Baker and Newton (2006) report both elite and sub-elite rugby players (*n* = 12) increase strength by ~12.5% over 4 years yet the ratio of gains from the first 2 years of training to the second 2 years was 0.6:1 highlighting the reduced magnitude over time. Baker (2008; 2013) 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., (2012) 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).

Recent studies have used larger samples of publicly available data in strength sports (Miller et al., 2018; Huebner and Perperoglou, 2019; Latella et al., 2020). Miller et al. (2018) examined 10 years of data from 700+ female weightlifters finding strength did not change meaningfully after the first 6 months of competition. Huebner and Perperoglou (2019) 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. (2020) examined powerlifters (*n* = 1897) reporting, similarly to Appleby et al. (2012), 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 more 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 (Thorndike, 1939; Robinson, 1950) 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 (Oldham, 1962; Tu and Gilthorpe, 2007). 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 participants (Bryk and Raudenbush, 1987).

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.

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 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). 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

After data 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 47±12 years.

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 supervisor to trainee ratio of 0.5:1 to 1:1 meaning there were never any more than two trainees maximum being trained in the facilities at any given time. Trainees typically 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 that was intended to allow participants to perform between four to six repetitions before reaching momentary failure as defined by Steele et al. (2017). 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 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 bottom of the eccentric, and avoiding excessive momentum at the top of the concentric. Participants progressed from exercise to exercise quickly as soon as they felt ready to do so, and typically with ~20 seconds rest between exercises. Thus, total session time was always <20 minutes. Participants training loads were progressed from between ~1-10% based on the machine being used, how far they exceeded the repetition/time under load range, and from the supervisor's appraisal of whether they were able to maintain continuous breathing, appropriate exercise form/posture, and the prescribed repetition duration. Lastly, participants typically trained in normal clothing.

Strength Outcomes

Due to the implementation of the standardized training protocols over time described above, we were able to operationalise training loads used during exercise sessions as our strength outcome in the present analysis. As all participants had completed leg press, chest press, and pulldown exercises in each training session the loads for these were examined. Participants trained using the same repetition duration and time under load/repetition range within which it was intended they would reach momentary failure. As noted, once participants exceeded the target time under load/repetition range they had their load progressed for the next session. Thus, load progression was 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 samples (Amrhein et al., 2019). 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. 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 (Amrhein et al., 2019; McShane et al., 2019). 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 (v 4.0.2; 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 were strength for each exercise (leg press, chest press, and pulldown) were the dependent variables. 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. Random intercepts and slopes for time for individual participants were included. We initially visually explored two models where log(time) was treated linearly, or as a second order polynomial. A random sample of 20 participants were drawn and leg press strength explored. Both models were fitted on this sample and the respective model predicted values were plot and compared with the raw values. The difference in fit when inspected visually (see https://osf.io/2j9ca/), and the respective R^2 values (see https://osf.io/6ca4t/), was negligible between the two 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

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

Level 2

$$\beta_{0j} = \gamma_{00} + U_{0\mathrm{j}}$$
$$\beta_{1j} = \gamma_{10} + U_{1\mathrm{j}}$$

We also examined models of the interaction effects of age as a continuous variable and sex thus formulating level 2 in these models as:

Level 2 (age)

$$\beta_{0j} = \gamma_{00} + \gamma_{01} age_{\mathrm{j}} + U_{0\mathrm{j}}$$
$$\beta_{1j} = \gamma_{10} + \gamma_{11} age_{\mathrm{j}} + U_{1\mathrm{j}}$$

Level 2 (sex)

$$\beta_{0j} = \gamma_{00} + \gamma_{01} sex_{\mathrm{j}} + U_{0\mathrm{j}}$$
$$\beta_{1j} = \gamma_{10} + \gamma_{11} sex_{\mathrm{j}} + U_{1\mathrm{j}}$$

All models were fit using the 'lme4' package (Bates et al., 2015) with Restricted Maximum Likelihood Estimation and Nelder-Mead optimisation (Nelder and Mead, 1965). Model summary tables were produced using the 'sjPlot' package (Lüdecke, 2020). Standardised beta coefficients using Gelman's (2008) 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. Model diagnostics were inspected on a random sample of 1000 participants to better facilitate visualisation using the 'performance' package (Lüdecke et al, 2020).

Data visualisation for the main model included calculation of model predicted values and 95% prediction intervals using the 'merTools' package (Knowles and Frederick, 2020) 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 fit the main models on the entire participant sample and then drew a further random sample of 1000 participants from the dataset. Then, using the main model, we calculated predicted values and intervals for the fixed effects from our model in this sample up to the maximum session number for which data was available in the main sample. Visualisation for the interaction models was done using 'sjPlot' with age interactions presented for the across a range of age values (30, 50, and 70 years), and for sex as separate curves (i.e., male and female). Interaction plots were presented as the model predicted values and 95% compatibility (confidence) intervals. All plots are presented on both the raw untransformed time scale, and on the common logarithmic scale. Additionally, for the main model's the fitted values of the 1000 participant sample for strength 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 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/7phu3/), 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 >250 weeks 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 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 (Lumley et al., 2002; Schmidt and Finan, 2018), and mixed models (Schielzeth et al., 2020; Knief and Forstmeier, 2020) are typically robust to deviation from normality assumptions.

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 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) clearly indicates that rapid strength adaptation typically occurs for the first year of resistance training before beginning to plateau. Standardised beta coefficients for log(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 2). Formal model summaries for each exercise are presented in table 1).

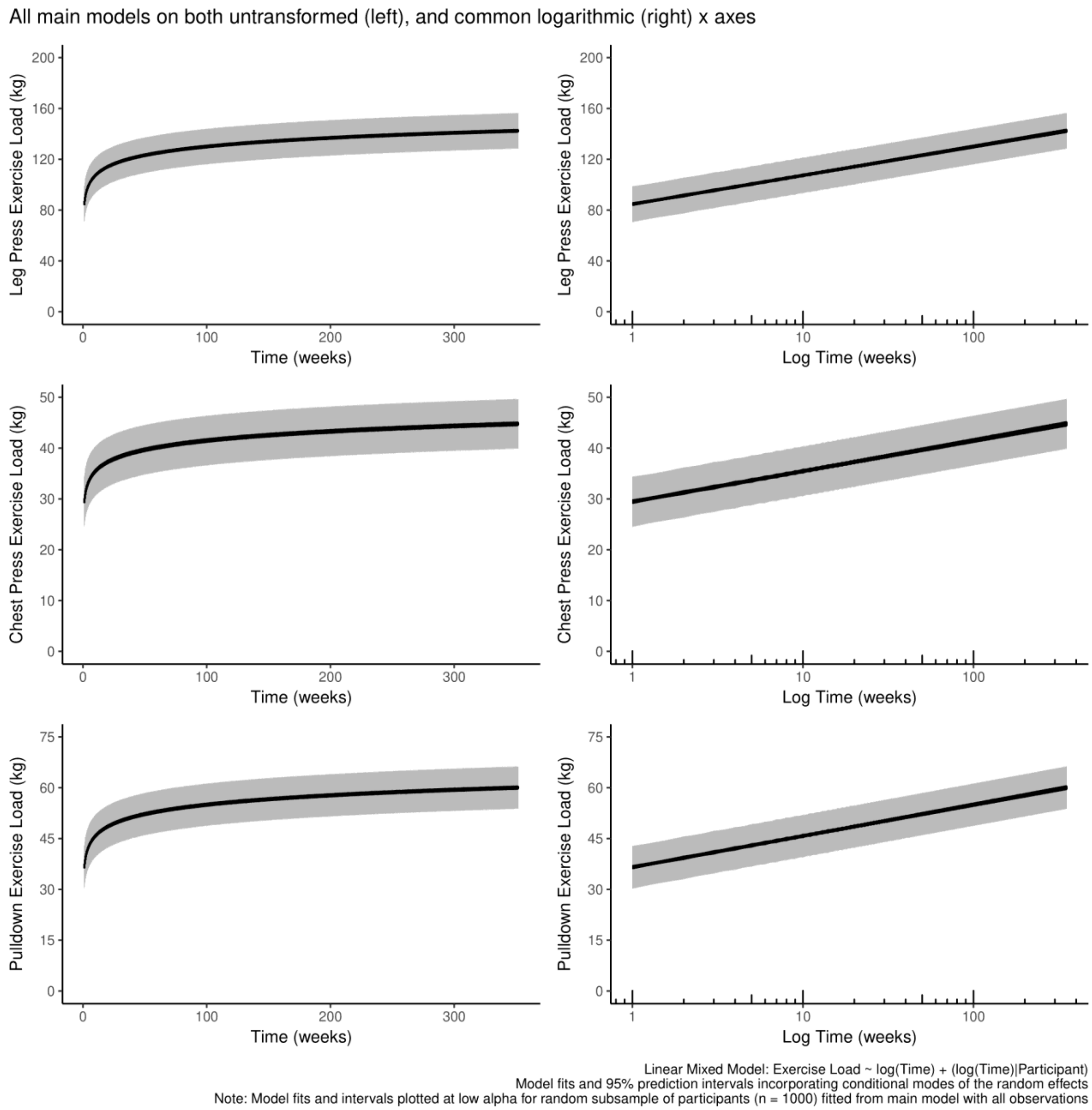

Figure 1. Main model fitted values (solid lines) and 95% prediction intervals (grey ribbons).

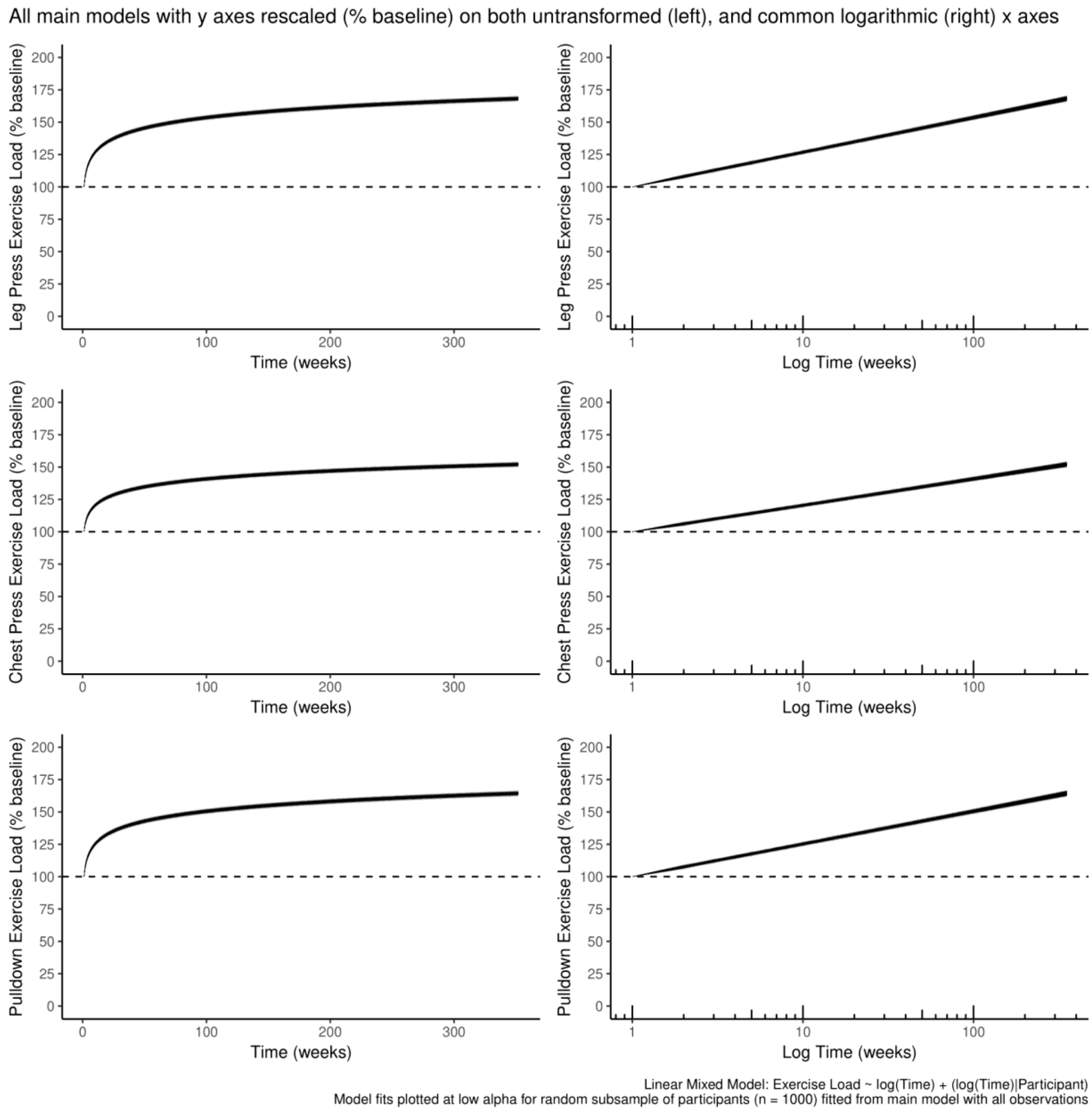

Figure 2. Main model fitted values rescaled as percentage of baseline strength values.

Table 1. Main model summaries

	Leg Press Exercise Load (kg)						Chest Press Exercise Load (kg)						Pulldown Exercise Load (kg)					
Predictors	*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	-0.68	84.17 – 85.14	-0.70 – -0.67	**<0.001**	**<0.001**	29.44	-0.45	29.26 – 29.62	-0.46 – -0.43	**<0.001**	**<0.001**	36.53	-0.60	36.31 – 36.75	-0.61 – -0.58	**<0.001**	**<0.001**
time [log]	9.85	1.46	9.70 – 10.00	1.43 – 1.48	**<0.001**	**<0.001**	2.61	0.92	2.56 – 2.67	0.89 – 0.94	**<0.001**	**<0.001**	4.01	1.25	3.95 – 4.07	1.23 – 1.28	**<0.001**	**<0.001**
Random Effects (Variances)																		
σ^2	99.30						12.57						20.32					
τ_{00}	812.65 $_{participant}$						123.84 $_{participant}$						165.16 $_{participant}$					
τ_{11}	64.07 $_{participant.log(time)}$						8.13 $_{participant.log(time)}$						11.52 $_{participant.log(time)}$					
ρ_{01}	-0.34 $_{participant}$						-0.19 $_{participant}$						-0.33 $_{participant}$					
ICC	0.92						0.94						0.91					
N	14182 $_{participant}$						14566 $_{participant}$						14274 $_{participant}$					
Observations	500028						529828						524285					
Marginal R^2 / Conditional R^2	0.110 / 0.926						0.049 / 0.940						0.093 / 0.922					

Sex Interaction

Sex impacted model intercepts across all exercises with males having greater strength at baseline and continuing across time (figure 3). Standardised intercepts showed a large effect of sex, and standardised beta coefficients most strongly supported an interaction effect with log(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. Formal model summaries for each exercise are presented in table 2).

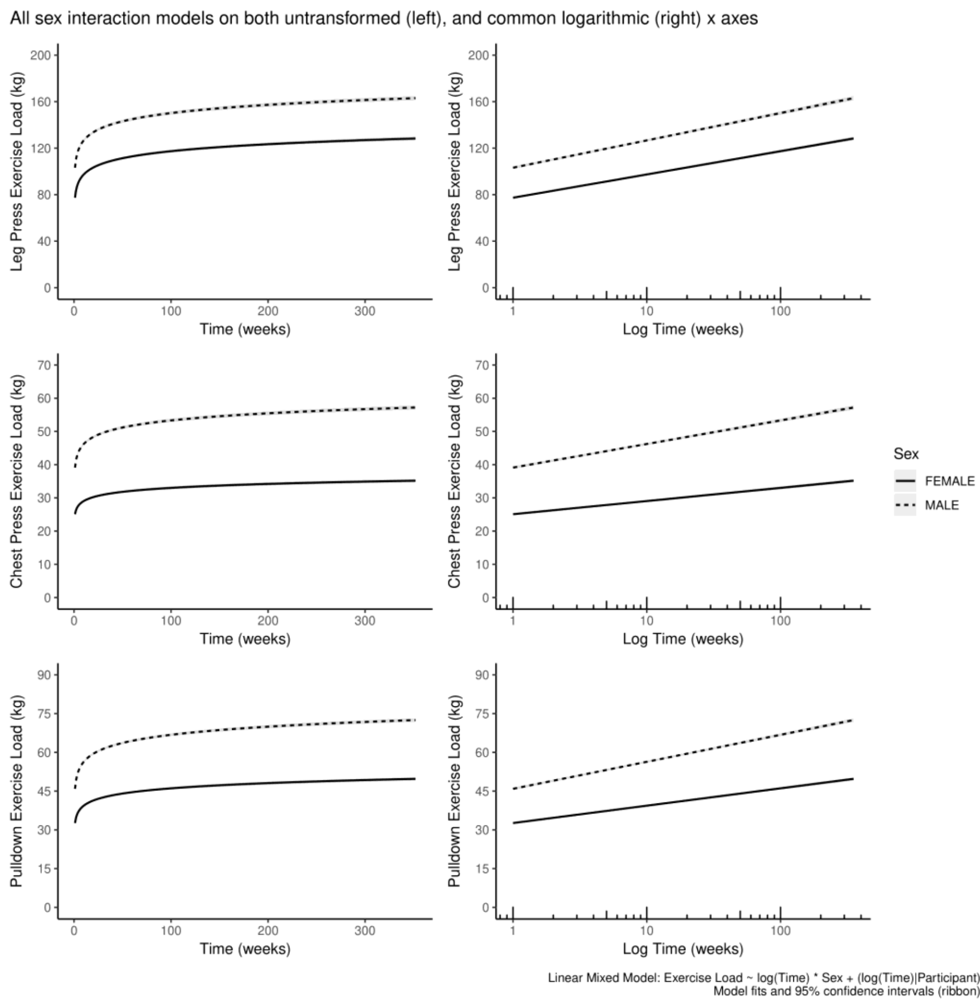

Figure 3. Sex interaction model fitted values and 95% compatibility (confidence) intervals

Table 2. Sex interaction model summaries

	Leg Press Exercise Load (kg)					
Predictors	*Estimates*	*std. Beta*	*CI*	*standardized CI*	*p*	*std. p*
(Intercept)	77.37	-1.02	76.33 – 78.40	-1.05 – -1.00	**<0.001**	**<0.001**
time [log]	8.69	1.34	8.37 – 9.01	1.28 – 1.40	**<0.001**	**<0.001**
Sex [male]	25.82	0.82	24.18 – 27.45	0.78 – 0.86	**<0.001**	**<0.001**
time [log] * Sex [male]	1.52	0.10	1.01 – 2.02	0.00 – 0.19	**<0.001**	**0.045**
Random Effects (Variances)						
σ^2	122.73					
τ_{00}	807.38 participant					
τ_{11}	66.92 participant.log(time)					
ρ_{01}	-0.49 participant					
ICC	0.89					
N	5121 participant					
Observations	257658					
Marginal R^2 / Conditional R^2	0.270 / 0.917					

	Chest Press Exercise Load (kg)					
Predictors	*Estimates*	*std. Beta*	*CI*	*standardized CI*	*p*	*std. p*
(Intercept)	25.08	-0.85	24.73 – 25.44	-0.88 – -0.83	**<0.001**	**<0.001**
time [log]	1.72	0.65	1.61 – 1.83	0.60 – 0.70	**<0.001**	**<0.001**
Sex [male]	14.03	1.14	13.47 – 14.59	1.10 – 1.17	**<0.001**	**<0.001**
time [log] * Sex [male]	1.36	0.40	1.19 – 1.54	0.32 – 0.48	**<0.001**	**<0.001**
Random Effects (Variances)						
σ^2	13.98					
τ_{00}	99.44 participant					
τ_{11}	7.94 participant.log(time)					
ρ_{01}	-0.49 participant					
ICC	0.89					
N	5267 participant					
Observations	277347					
Marginal R^2 / Conditional R^2	0.441 / 0.940					

	Pulldown Exercise Load (kg)					
Predictors	*Estimates*	*std. Beta*	*CI*	*standardized CI*	*p*	*std. p*
(Intercept)	32.64	-0.97	32.21 – 33.08	-1.00 – -0.95	**<0.001**	**<0.001**
time [log]	2.92	0.98	2.79 – 3.05	0.92 – 1.03	**<0.001**	**<0.001**
Sex [male]	13.25	1.00	12.56 – 13.94	0.96 – 1.04	**<0.001**	**<0.001**
time [log] * Sex [male]	1.62	0.40	1.42 – 1.83	0.32 – 0.48	**<0.001**	**<0.001**
Random Effects (Variances)						
σ^2	23.63					
τ_{00}	144.72 participant					
τ_{11}	11.04 participant.log(time)					
ρ_{01}	-0.58 participant					
ICC	0.86					
N	5182 participant					
Observations	273058					
Marginal R^2 / Conditional R^2	0.420 / 0.917					

Age Interaction

Age impacted model intercepts across all exercises with reduced strength with increasing age baseline and which continued across time (figure 4). Standardised intercepts showed that the effect of age was relatively small. 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).

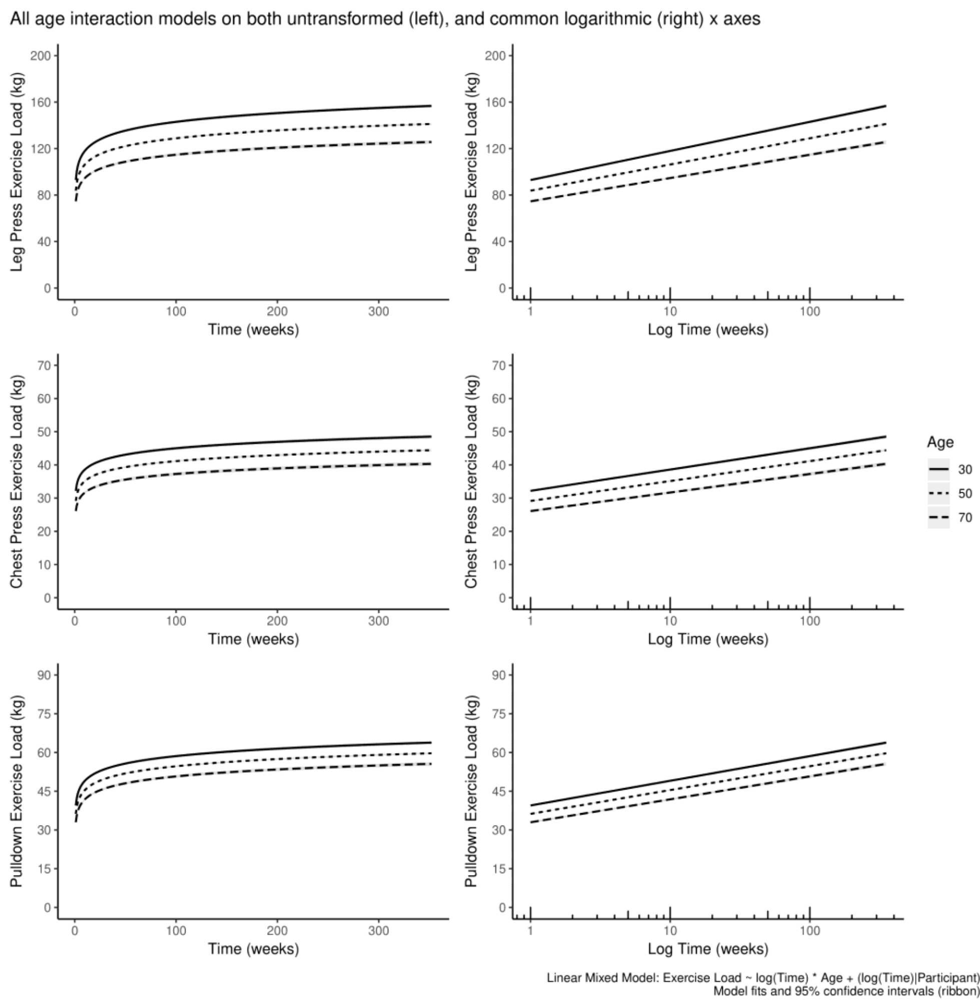

Figure 4. Age interaction model fitted values and 95% compatibility (confidence) intervals

Table 3. Age interaction model summaries

	Leg Press Exercise Load (kg)						Chest Press Exercise Load (kg)						Pulldown Exercise Load (kg)					
Predictors	*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)	106.67	-0.70	104.79 – 108.56	-0.71 – -0.68	**<0.001**	**<0.001**	36.76	-0.45	36.03 – 37.48	-0.47 – -0.44	**<0.001**	**<0.001**	44.37	-0.60	43.51 – 45.22	-0.62 – -0.59	**<0.001**	**<0.001**
time [log]	12.50	1.46	11.89 – 13.11	1.43 – 1.48	**<0.001**	**<0.001**	3.06	0.92	2.84 – 3.27	0.89 – 0.94	**<0.001**	**<0.001**	4.37	1.26	4.11 – 4.63	1.23 – 1.28	**<0.001**	**<0.001**
age	-0.46	-0.16	-0.50 – -0.42	-0.17 – -0.15	**<0.001**	**<0.001**	-0.15	-0.12	-0.17 – -0.14	-0.14 – -0.11	**<0.001**	**<0.001**	-0.16	-0.11	-0.18 – -0.15	-0.13 – -0.10	**<0.001**	**<0.001**
time [log] * age	-0.05	-0.12	-0.07 – -0.04	-0.15 – -0.09	**<0.001**	**<0.001**	-0.01	-0.04	-0.01 – -0.00	-0.06 – -0.02	**<0.001**	**<0.001**	-0.01	-0.04	-0.01 – -0.00	-0.07 – -0.02	**0.006**	**0.001**
Random Effects (Variances)																		
σ^2	99.30						12.57						20.32					
τ_{00}	780.26 participant						120.26 participant						161.07 participant					
τ_{11}	63.53 participant.log(time)						8.12 participant.log(time)						11.51 participant.log(time)					
ρ_{01}	-0.36 participant						-0.20 participant						-0.34 participant					
ICC	0.91						0.94						0.91					
N	14182 participant						14566 participant						14274 participant					
Observations	500028						529828						524285					
Marginal R^2 / Conditional R^2	0.149 / 0.926						0.071 / 0.940						0.110 / 0.922					

Survivorship Bias?

When models were refit on only those participants with ≥250 sessions model coefficients did not differ drastically from the main models except for attenuated standardised estimates (see supplementary materials https://osf.io/4xzfs/). Model fitted values qualitatively showed the same shape to the time-series (see supplementary materials https://osf.io/578xu/) 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(time) there were essentially no relationships for either intercepts of slopes (see supplementary materials https://osf.io/vkpgx/). Thus, we were confident that our models appropriately reflected the effects of participation in minimal dose resistance training over time absent survivorship bias.

Discussion

The results of this study demonstrate that, despite substantial initial gains in strength during the first year of participation in minimal dose resistance training, a plateau in growth occurs with gains slowing over continued participation. A linear-log model was a strong fit for this relationship. Unsurprisingly, both sex and age impacted model intercepts (i.e. baseline strength) with males and younger adults exhibiting greater strength than their female and older comparators. However, the interaction of sex and age with time was minimal, with largely similar slopes (i.e., shapes of growth curves over time) and plateaus. Using appropriate longitudinal growth modelling, this study supports previous suggestions of the *plateau* or *ceiling* phenomena for strength resulting from resistance training.

Why a plateau in strength after ~1 year of participation in minimal dose resistance training 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 (Fisher et al., 2018; Buckner et al., 2020). 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 experience (Ralston et al., 2017). More directly examining this, Hass et al. (2000) 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 measurement (Buckner et al., 2019), 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 this, we applied the same longitudinal growth model to a random sample of 10,000 lifters (limited to exploring totals [kg] for squat/bench press/deadlift competition; (see https://osf.io/de3ws/ and https://osf.io/8jx3e/) from the Open Powerlifting dataset (https://openpowerlifting.gitlab.io/opl-csv/introduction.html). It seems 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 (Swinton et al., 2009; Shaw et al., 2020). In this exploratory powerlifting model relative gains were 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 training. However, despite this, we still observe a plateau after ~1 year of competition questioning whether the typical application of variation through periodisation by powerlifters can really enable continued strength adaptation with time. Thus, although some evidence suggests in the short-term (6 to 36 weeks) periodization might enhance strength gains (Williams et al., 2017), given sufficient time (≥1 year) plateaus may be unavoidable irrespective of training approach. Collectively this evidence lends support to early plateaus in strength with resistance training as being a robust phenomenon.

The observation that strength appears to plateau over roughly similar timeframes, even across different populations and training approaches, presents interesting practical implications. In support of recommendations from a public health perspective (Steele et al., 2017; Fisher et al., 2017; Bull et al., 2020), relatively simple minimal dose resistance training approaches can produce substantial strength gains which can be easily maintained over the long-term. Further, minimal dose approaches may offer utility to previously trained populations who may still produce small gains from their use (Androulakis-Korakakis, 2020), 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 ageing (Rantanen et al., 1998; Frontera et al., 2000; Nahhas et al., 2010; Dodds et al., 2014; Kemmler et al., 2018). 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 Signorile (2011).

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, 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 presence of a plateau in strength development (as we have done so with the Open Powerlifting 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 this 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.

Conclusion

Substantial strength gains are possible with the use of a minimal dose resistance training approach. Though, these begin to plateau after ~1 year of training with little impact from sex or age on the emergence of this plateau. 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.

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Data and Supplementary Material Accessibility

All materials, data, and code are available on the Open Science Framework project page for this study https://osf.io/jn6ay/

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