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Research Article

Getting a Grip on Secular Changes: Age–Period–Cohort Modeling of Grip Strength in the English Longitudinal Study of Ageing

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Abstract

Background: Grip strength is a popular and valuable measure in studies of physical functional capabilities in old age. The influence of historical trends and differential period-specific exposures can complicate the interpretation of biomarkers of aging and health and requires careful analysis and interpretation of aging, birth cohort, and period effects. This study evaluates the effects of aging, period, and cohort on grip strength in a population of adults and older adults.

Methods: We use more than 27 000 observations for individuals at least 50 years of age, born in approximately 1910–1960, from the English Longitudinal Study of Ageing to examine a variety of multilevel and cross-classified modeling approaches to evaluate age, period, and cohort effects. Our results extended Hierarchical Age–Period–Cohort modeling and compared our results with a set of 9 submodels with explicit assumptions to determine the most reliable modeling approach.

Results: Findings suggest grip strength is primarily related to age, with minimal evidence of either period and/or cohort effects. Each year's increase in a person's age was associated with a 0.40-kg decrease in grip strength, though this decline differs by gender.

Conclusions: We conclude that as the population ages, grip strength declines at a systematic and predictable rate equal to −0.40 kg per year (approximately −0.50 kg for men and −0.30 kg for women) in residents of England aged 50 and older. Age effects were predominant and most consistent across methodologies. While there was some evidence for cohort effects, such effects were minimal and therefore indicative that grip strength is a consistent physiological biomarker of aging.

Keywords: Age–period–cohort modeling, Grip strength, Secular change

Grip strength is an overall indicator of general health status and an indicator of many specific health outcomes including cognition (1–3). Grip strength is a reliable marker of aging across the life course (4) and predicts mortality and disability (5–8). It also predicts mortality after accounting for a measure of body composition, such as body mass index (BMI), weight, and fat mass, as well as related conditions such as diabetes and coronary artery disease (6,9–11); in several of these studies, the findings were particularly pronounced for men. Grip strength also improves prediction of cardiovascular and all-cause mortality even after accounting for walking speed, standing balance, and risk for falls measured by the timed up and go task (12,13). A recent study examining changes in grip strength in a sample of older adults from Germany, Sweden, and Spain found both cohort and period trends in grip strength (14). Changes in population average grip strength could portend changes in mortality and disability. Obtaining estimates of such secular or cohort trends will allow societies to predict and prepare for future health outcomes. While the identification of cohort-related trends is central to considerations of cognitive aging (15), methods commonly used to examine aging-related decline are insufficient to derive such norms. In light of these methodological concerns, we evaluated a variety of methods to model age changes and cohort differences in grip strength. We first outline current research on grip strength and describe the importance of grip strength, particularly as an indicator of age-related health. We then discuss Age–Period–Cohort (APC) models and analyze English Longitudinal Study of Ageing (ELSA) data using these alternative methodological approaches.

Grip Strength

Grip strength provides an objective and convenient alternative to self-reports of health. In a prospective study of men aged 45–68 years, Rantanen et al. (6) found that baseline measures of grip strength predicted overall disability and ability to complete tasks of daily living 25 years later. Sasaki et al. (9) found that grip strength predicted all-cause mortality as well as mortality from heart disease and stroke. In fact, grip strength predicts all-cause mortality and mortality due to cardiovascular conditions, in a variety of international settings. Leong et al. (16) found that grip strength was as good as or better at predicting mortality from certain cardiovascular conditions than systolic blood pressure. In addition to physical health, grip strength is associated, longitudinally and cross-sectionally, with changes in cognition. A decrease in grip strength is associated with a decline in a variety of cognitive measures (2,3). Grip strength's predictive ability is impressive enough that some have called it a biomarker for aging (17).

Correlates of grip strength arise early, with birth weight, prepubertal height gains, and pubertal growth positively associated with midlife grip strength (18). Sayer et al. (19) found that birth weight predicted grip strength over 60 years later, and Kuh et al. (20) found that birth weight predicted men and women's grip strength in middle age regardless of their current or former socioeconomic status. Physical activity can help to preserve grip strength in older ages, with beneficial effects after age 60 (21). Dodds et al. also noted that leisure physical activity during midlife is associated with later grip strength (as opposed to concurrent grip strength), suggesting a protective effect of physical activity. A study of the effects of physical activity in women found that more active women had greater grip strength (22).

These early predictors of grip strength have themselves been subject to change over time. Given that these predictors and correlates of grip strength have changed, it is plausible that grip strength has also undergone secular changes as well. By secular change we mean long-term systematic changes that could be due to an aging population, changes in cohorts, or period effects that alter an outcome for all (or a significant subset) of the population. Looking at the aforementioned correlates of grip strength, in the UK cohort differences in birth weight have been noted, with a shift toward heavier birth weights (23). Additionally, the timing of pubertal height changes has shown a secular trend, at least in men (24), and the timing of puberty, in general, has changed (25). Similarly, there is evidence that leisure-time physical activity for adults has increased (which would suggest potential increases, in grip strength (26)). However, that same study also found declining levels of physical activity in children and declines in work-related physical activity in adults.

While we have established the possibility for changes in grip strength, the direction of such changes may be positive, negative, or nil. For example, the changes predicted by secular trends in physical activity could be positive or negative depending on the kind of physical activity measured. Research regarding secular trends in grip strength is mixed. In a review of literature on US and Canadian children, Silverman (27) found little evidence for secular change. In a second US study, Loprinzi (28) found no evidence of secular changes in grip strength in a sample aged 6–80 (in a 4-year span from 2011 to 2014). Christensen et al. (29) found no evidence of change in a Danish sample of 93- and 95-year-old individuals born 10 years apart. Recently, the research found later-born cohorts in Norway were stronger than earlier-born cohorts (30). The differences between cohorts were attributed to differences in socioeconomic status, education, height, and weight. In contrast, using ELSA data, Dodds et al. (31) reported a difference in grip strength in same-age individuals who were assessed between 2004 and 2013, with weaker grip strength in more recently born cohorts. Taken together there is evidence for positive, negative, and stagnant secular trends.

APC Models

Secular trends can be identified, and elaborated, using APC modeling. Teasing apart age, period, and cohort effects is important, yet the search for suitable APC models is contentious. In any APC model, a perfect linear dependency exists among the combination of age, period, and cohort. For example, if you know that a person was tested in 1990, and that they were 20 years old, they were necessarily born in 1970 (ie, Cohort = Period − Age). This dependency leads to indeterminacy in statistical models that try to use all 3 to predict an outcome. Attempts to find mechanistic solutions have been described as an "unholy quest" (32) and a "futile quest" (33,34). Those targeted by criticism say that they have not claimed to have found the "holy grail" of modeling (35). Regardless of the kind of quest APC modeling is, Arthurian or Monty Pythonic, the general implication is clear: A universally applicable APC model is beyond our grasp (32).

Aims of this Study

The goal of this study is to evaluate secular changes in grip strength, using the ELSA (36). To separate the demographic sources that are contenders to explain potential secular trends—the age, period, and cohort effects—we implement a variety of APC models. The application of a number of APC approaches allows the evaluation of the robustness of our findings across different analytic procedures and under a variety of methodological assumptions.

Method

Sample

This study analyzes data from the ELSA (36), a longitudinal, population-representative panel survey of English adults aged 50 and older and their spouses. Our sample comes from Waves 2, 4, 6, and 8. Only in the even-numbered waves were relevant clinical health data collected, including measures of grip strength. Data were collected during 2004, 2008, 2012, and 2016, starting at the beginning of each year and continued through the next year. For this study, we analyzed the core members with health data. In total, there were 11 181 participants, providing 25 964 observations. About 10 684 participants had complete data on all relevant measures. To account for missing data, we used multiple imputation. The 3 earlier waves have sample sizes approximately double the sample size of the last wave. Budgetary constraints limited the collection of data in the final wave. Demographics are presented in Table 1. Race was recorded as binary White/not White. Across the waves, the average age was near the late 60s, the percentage of male participants was approximately 45% and the percentage of the sample that was White was approximately 97%.

ELSA participants gave informed consent. The data repository for the ELSA states: "The ethical approval for all the ELSA waves was granted from the National Research and Ethics Committee. The ELSA data were made available through the UK Data Archive." ELSA data can be found at the UK data service, with access instructions found at https://www.elsa-project.ac.uk/accessing-elsa-data.

Multiple Imputation

Missing data were imputed using the mice package in R version 4.0.2 (37). All terms included in any APC model were also included in the imputation model. When exact collinearity would arise, one term was left out (eg, age might be left out of an imputation model with period and cohort). Because of the exact linear dependency among variables, so long as the other terms are included, the excluded term can still be appropriately modeled. For cases missing height data, any previous height measures for that person were averaged, and that average was used as the value for the missing height measurement. All other missing heights were imputed in the multiple imputation procedure. Imputed height was then used to calculate missing BMI values. This procedure was used to prevent unrealistic levels of variance within-person, as adult height is highly stable (although it can decline slightly (38)). A total of 20 multiply imputed data sets were created using 20 iterations of the mice (37) algorithm for each.

Measurements

Grip strength

Grip strength was measured in the ELSA sample by taking 3 measures of both the dominant and nondominant hands of the participants. Grip strength was measured as the isometric handgrip strength in kilograms using a Smedley dynamometer. In the present analysis, we used the maximum recorded grip strength from the dominant hand. This is the same method used by Beller et al. (14).

Body mass index

BMI was obtained either via self-report or via measurements of a participants' height and weight. For the final wave of ELSA data, height was not measured and so this wave did not include a BMI measure and was imputed as described previously.

Table 1. Demographics for the English Longitudinal Study of Ageing Waves

Wave	Average Age (years)	Percent Male	Percent White	Sample Size
2004	67	45.02	98.30	7666
2008	67	44.95	97.48	8218
2012	68	44.61	97.01	7730
2016	71	44.41	97.73	3479

Self-reported health

Participants were asked to report their overall health. They reported their perceptions of their general health on a scale ranging from 1 to 5, with a score of 1 being "excellent" and a score of 5 being "poor," thus lower scores correspond to better health.

Exercise

In our study, respondents were asked questions about their frequency of participation in light, moderate, and vigorous physical activities. Scores ranged from 1 (more than once a week) to 4 (hardly ever or never), with lower scores indicating more frequent physical activity in each category.

Age, period, and cohort

Year of birth was used as the cohort measure. Period was taken as the survey year of data collection. In the raw data, participants aged 90 and older had their cohorts and ages collapsed to single numbers (eg, all individuals 90+ were given an age of 90). Verified ages were also occasionally missing. To account for both issues, the date of birth was subtracted from the period to calculate the age for all participants. The date of birth variable came from a processed version of the raw data provided by the gateway to global aging and proved to be more consistent than the version in the raw unprocessed data. This procedure resulted in no missing data for age, period, or cohort.

We further centered age, period, and cohort prior to imputation, and all other variables after imputation, thus the intercept represents the predicted grip strength of an individual of average age, health, BMI, and physical activity (in our data), the quadratic age variable was created after centering the original age variable.

Models

All analyses were carried out in R version 4.0.2. We evaluated 2 APC modeling approaches, each with multiple subapproaches. The first method used was the Hierarchical Age–Period–Cohort (HAPC) model described by Yang and Land (39) and used by Beller et al. (14). HAPC models use cross-classified modeling to account for the effects of age, period, and cohort simultaneously. Cross-classified models are a type of random effects model, similar in principle to multilevel models or hierarchical linear models. In these models, the distinct effects of each group (period or cohort in our models) can be modeled. Cross-classified means that in a given grouping (eg, a specific period), participants can be members of multiple groups in the other category (eg, multiple cohorts), and, importantly, that the converse is true (ie, in a given cohort, participants are members of multiple periods). Yang and Land initially defined a model that includes a squared term for age, as does the model used by Beller et al. (14), and so we include the term here as well. We added a random intercept component to account for the clustering of observations within-individual. As the ELSA data are longitudinal, this latter adjustment accounts for the design differences between our study and the study of Beller et al. (14). This model can be seen in eqn (1) in Supplementary Appendix. In Supplementary Appendix, we also provide an adaptation of this model (40). We make the assumption that the period effects in our data represent random fluctuations, and there is no systematic trend in grip strength due to period, further modifications were made in light of model-fitting considerations, a full treatment is given in Supplementary Appendix. Given the early developmental precursors of later-life grip strength (some as early as birth), we conceptualize these factors collectively as cohort effects, rather than period effects. Although one cannot avoid APC confounding, we believe prioritizing cohort effects over period effects is justified based on previous developmental studies that emphasize factors that occur early in the life span as shown previously in our review of the literature. Thus, we fit a modified HAPC model, which includes a linear and quadratic fixed effect for cohorts (instead of a random cohort effect as in the original HAPC model) and random intercepts for individuals and periods. Although the quadratic age component is not necessary for this model, it was statistically significant in the work of Beller et al. (14), and so we kept it in our HAPC and modified HAPC models. This model is eqn (2) in Supplementary Appendix. Results are also given in Supplementary Appendix to conserve space.

Our second method of analysis makes more agnostic assumptions regarding the effects of age, period, and cohort. We fit a series of 9 nested models. In the first set of models, we include control variables and only one of age, period, or cohort. In the next 3 models, we use the 3 unique bivariate combinations of age, period, and cohort. Last, we fit a final set of 3 models, identical to the 3 bivariate APC models, except that they also include the interaction of the included APC variables. The first set of models (Models 3–5) is equivalent to making the assumption that only one of age, period, or cohort affects grip strength. The next 3 models (6–8) assume that only 2 of the 3 APC variables affect grip strength and that the third, omitted, variable does not. The final 3 models make the same assumption as Models 6–8 but allow for the included APC variables to moderate each other. The quadratic age effect is not included in this analysis as the age variable is not included in all models. This approach is flexible and allows one to observe all possible combinations of the 3 variables. These models are summarized in eqns (3–11) in Supplementary Appendix (in all equations, the control variables, exercise, health, and BMI, are omitted, but included in the actual analysis). All multilevel models were fit in R (41) using the lme4 (42) package.

Results

HAPC Model

The first model fit was the HAPC model from eqn (1) in Supplementary Appendix. The comparison between our results and Beller et al.'s (14) results is given in Table 2. It was necessary to modify our original model. Our original model accounted for clustering due to repeated observations; however, this model resulted in zero variance in the cohort random effects and singular model fits. The largest effect is for age, which will be a consistent result across analyses. The cohort and period random effect standard deviations were calculated as the square root of the mean of the respective variances from the multiple imputation model results. Every fixed effect in our model was statistically significant ($p < .001$), except for the age^2 effect. We plot the period and cohort random effects in Figures 1 and 2. There are some small indications of linearity in the period residuals, but random noise in the cohort residuals.

Multiple Model Approach

In our second analysis, we use the same control variables as above and exactly the same data. We fit each model to each imputed data set and pooled the results using the same methods available in the mice package. To calculate degrees of freedom for p values, we used published formulas (43).

We fit 9 models. First, we fit one model for each main effect of age, period, and cohort. Next, we fit 3 models with pairs of main

Table 2. Comparison of ELSA HAPC Results to Beller's Results

Coefficient	England (ignoring nesting)	Germany	Sweden	Spain
Intercept	35.07	37.33	36.52	29.56
Age (in years)	−0.346	−0.381	−0.360	−0.402
Age^2	−0.002	−0.009	−0.007	−0.006
Cohort *SD*	0.42	0.65	0.06	0.77
Period *SD*	0.18	0.30	0.80	0.53

Notes: HAPC = Hierarchical Age–Period–Cohort; ELSA = English Longitudinal Study of Ageing. The intercept for this model shows that a person of average age would be expected to have a grip strength of approximately 35 kg. For every additional year of aging, grip strength declines by approximately a third of a kilogram. While there is a small quadratic effect for age, such that grip strength declines at an accelerating pace with age, it is small enough that after 20 years of aging grip strength would decline by less than 1 additional kilogram. The cohort and period standard deviations are the standard deviations of the random effects for cohort and period, so a typical cohort effect would be expected to be within 0.42 kg of the overall population average, and the typical period effect would be expected to be within 0.18 kg of the overall population average.

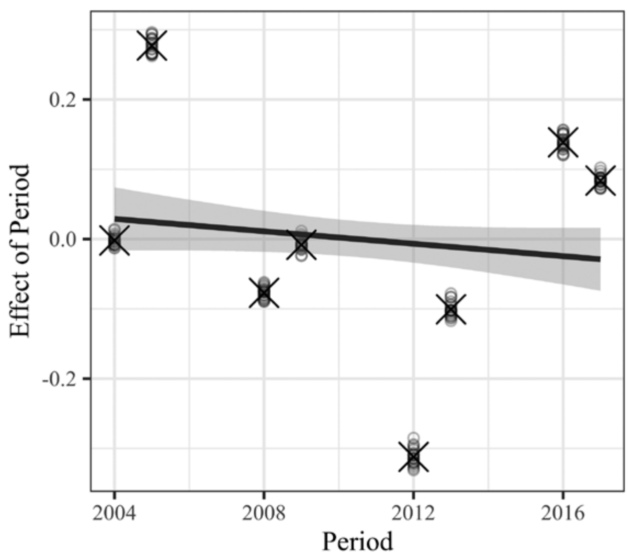

Figure 1. Individual points represent random-effects estimates (average residual for a given period) from individual imputations. Each cluster of points is therefore comprised of 20 points, each an estimate from a given imputation. The X-shaped points represent the average across all 20 imputations. *Note:* Because of the assumptions inherent in the Hierarchical Age–Period–Cohort model, estimated effects are potentially artefactual.

effects of age, period, and cohort. Finally, we added the interaction effects for each pair. Table 3 displays the results. The interaction terms were not statistically significant in any model. In the separate models for age, period, and cohort, we find a relatively large effect for age and smaller effects for period and cohort (approximately 10%–15% smaller). When period or cohort is added to a model with age, there is minimal change in the age coefficient, but the coefficients for period and cohort are no longer significantly different from 0. In all models including age, a single-year increase in a person's age leads to an approximately 0.40-kg decrease in their grip strength. The coefficients for cohort and period are not as consistent. Period has effects ranging from nonsignificant at approximately 0 to statistically significant (and relatively large) at −0.41. Similarly, the cohort has effects ranging from −0.04 to significantly positive at 0.40. In the models separated by gender (Supplementary Appendix), the age effect for men was substantially greater than (~1.5×) the effect for women.

Discussion

We have examined trends in grip strength using models developed to disentangle (as best as possible) age, period, and cohort effects. However, we note that it is impossible to conclusively disentangle these effects without either clear knowledge about the nature of one or more of the effects or without making strong assumptions. Secular trends in grip strength have been observed in the ELSA data prior to our study (31). These trends could be due to an aging population,

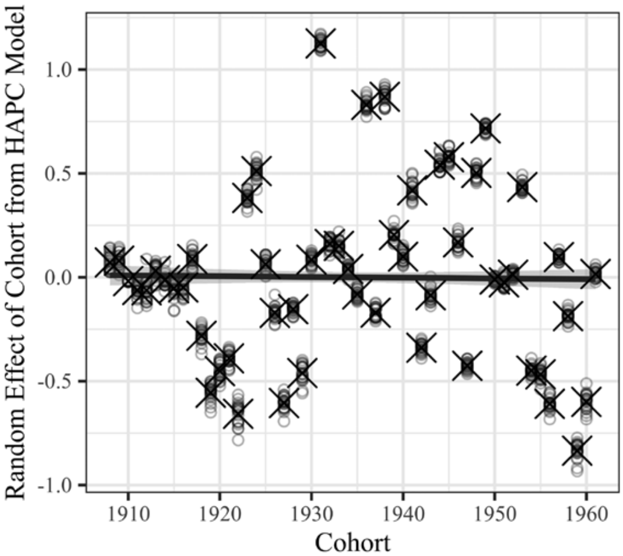

Figure 2. Individual points represent random-effects estimates (average residual for a given cohort) from individual imputations. Each cluster of points is therefore comprised of 20 points, each an estimate from a given imputation. The X-shaped points represent the average across all 20 imputations. *Note:* Because of the assumptions inherent in the Hierarchical Age–Period–Cohort model, estimated effects are potentially artefactual.

period, or cohort effects or some mix of these. In all models that included age, and in every study in which age was a factor, there is a clear and unambiguous effect for age. Furthermore, we have quantified that decrement, across demographic categories within the ELSA data, at approximately 0.40-kg reduction per year, in a sample aged 50 to 90 and older years.

Our HAPC model largely replicated Beller et al., who use data from the United States (Health and Retirement Study (14)). Looking at these random effects, our random effects for the period are smaller than those found previously, whereas, for our cohort effect, variability is larger than that found in Sweden but smaller than that found in other nations. Our fixed effects were largely similar to those found by Beller et al. An initial conclusion one might draw regarding the difference in random effects is that the effect of period and cohort is different in different countries. This is in line with recent research (44) that found differences in cohort effects when comparing a number of European countries, including the United Kingdom. Such a finding is interesting and is a reminder of the limitations of generalizability of any one set of results, even to otherwise similar contexts. However, in light of the limitations of HAPC modeling, an alternative explanation presents itself, namely that such effects may be due to modeling artifacts (34). In particular, the presence of linear trends in cohorts or periods violates the assumptions of the HAPC model, as Beller et al. found such trends in their cohort and period effects, it is unlikely that the HAPC model is appropriate for this research question. Unfortunately, if such effects are identified in an HAPC model, it is difficult to discern whether the cohort and period effects reflect secular trends in grip strength or are simply artifacts of a specific model interacting with the structure of a particular data set (eg, number of cohorts relative to periods). It is important to note that what we observe (and what Beller et al. observe) bears a striking similarity to effects presented in the work of Bell and Jones (34,45). Specifically, we found a small linear period effect and generally random noise for cohorts in data with relatively few periods and relatively many cohorts. Bell and Jones (45) show these findings can occur due solely to how our data are shaped (ie, the number of periods vs the number of cohorts) regardless of actual APC effects.

To provide expansion and different approaches compared to the HAPC model, we presented a series of 9 models. We acknowledge that these models cannot definitively differentiate between age, period, and cohort effects in these data. This statement may seem

Table 3. Results of 9 APC Models

Intercept	30.94***	30.91***	31.17***	30.94***	30.94***	30.94***	31.53***	30.94***	30.86***
Age	−0.40***			−0.41***	−0.40***		−0.41***	−0.40***	
Period		−0.36***			−0.01	−0.41***		−0.01	−0.41***
Cohort			0.32***	−0.01		0.40***	−0.04		0.40***
Age × Cohort							0.01		
Age × Period								0.00	
Period × Cohort									0.00
BMI	0.12	0.17	0.15	0.12	0.12	0.12	0.10	0.11	0.11
Health	−0.58**	−0.74***	−0.92***	−0.58**	−0.58**	−0.58**	−0.57**	−0.58**	−0.57**
Light exercise	0.08	−0.01	0.07	0.08	0.08	0.08	0.1	0.09	0.09
Moderate exercise	−0.50**	−0.61**	−0.73***	−0.50**	−0.50**	−0.50**	−0.46*	−0.49*	−0.48*
Vigorous exercise	−0.28	−0.38 *	−0.46 *	−0.28	−0.28	−0.28	−0.27	−0.28	−0.27
Intercept variance (all)	9.55	10.33	9.44	9.55	9.55	9.55	9.55	9.56	9.57

Notes: APC = Age–Period–Cohort; BMI = body mass index. In these models, an "average person" (ie, a person with average scores on all variables) would have an expected grip strength of approximately 31 kg. Age consistently decreases grip strength by about 400 g per year. Period and cohort have varying effects. A 1-year change in period causes either a 410-g decline in grip strength or a 10-g decline in grip strength. Similarly, a 1-year increase in birth cohort causes parallel gains (or losses) in grip strength. The health and exercise variables are coded such that lower scores are better. The intercept variance is between-person and suggests that a typical person's grip strength intercept (over repeated measures) would be within approximately 10 kg of the population average. *$p < .05$; **$p < .01$; ***$p < .001$.

like a limitation, and it is, however, logical and not a methodological limitation; an impediment that is present in every APC analysis. Each model provides a view of the data through a lens that makes strong and explicit assumptions. For example, the first model, which only has an effect on age, makes the clear and strong assumption that cohort and period have no effect on grip strength. Likewise, the model with only period and cohort makes the strong assumption that age has no effect on grip strength. Some models seem more plausible than others (it seems unlikely that age has no effect on grip strength); models must be chosen based on theoretical justifications and not model fit alone. One advantage to this set of models is that it makes these choices explicit. As the field of APC modeling advances, the requirement for theoretical justification and explication of constraints should become routine. Recent advancements in this area are a positive step in this direction (46).

Although the effect of age is certainly much larger than the other potential effects, and an aging population is certainly likely to see a decline in grip strength, there is still room for a cohort or period effect. Enough of our models showed evidence for one or the other that it is difficult to eliminate either one of the 2 effects. Based primarily on prior literature, cohort effects seem more plausible than period effects. For example, few interventions appear to have a direct and immediate impact on grip strength, whereas many predictors of grip strength are present at birth or childhood. That predictors of grip strength manifest early in development suggests that later-life influences, such as would cause period effects, may be less plausible. Some might argue that there are period effects that only affect individuals of particular ages (eg, children in utero during a famine). However, the interaction of a period and age effect is indistinguishable, on logical grounds, from a cohort effect, as only members of a particular cohort will manifest the effect.

Returning to our results, after accounting for age, there appears to be a small quadratic cohort effect (Supplementary Appendix). This effect was such that we would be expected to be past the "peak" of the cohort effect. In essence, going forward we might expect gradually weakening cohorts, and this weakening may accelerate. While this finding may sound alarming, the effect in question is small enough to round to zero at 2 decimal places, when the cohort is on a year scale and grip strength is measured in kilograms. A unit increase in squared cohort leads to less than a 10-g decline in grip strength. In contrast, a year of aging (for the age group studied) leads to a 400-g decline in grip strength.

We would advise future research to focus on accommodating and mitigating the effect of aging on grip strength, as well as an examination of the modifiable causes of age-related declines in grip strength, particularly those that may be amenable to intervention or prevention efforts. Furthermore, we should expect a weakening population, with heightened levels of disability and injury, as the population ages. Given previous research examining the relationship between cognition and grip strength (2,3), cohort and period-related differences might be important. However, in this study, we found such small period and cohort effects for grip strength, we would expect the effect of cohort and period to be virtually undetectable. With that consideration in mind, we would expect an increase in cognitive impairment as the population ages (an age effect), though this finding does not rule out the possibility of shifts in cognitive abilities due to other processes (eg, the Flynn effect (47)).

Limitations

The primary limitation of this study is the ambiguity of APC modeling. The HAPC model has been subject to a variety of criticisms (34,40,48). Succinctly, these authors argue that the HAPC model does not solve the aforementioned APC confounding, and the assumptions inherent in the HAPC model are violated if there is a nonrandom period or cohort effect. The fundamental assumption of the HAPC model is that the effect of period and cohort can be modeled as random effects. This assumption is also the primary limitation of the HAPC model, because effects modeled as random should be truly random. If we anticipate structure in the effect of period or the effect of cohort (eg, an increase in scores due to cohort differences), a model that considers the effect of period to be random will be an inaccurate model of our proposed hypothesis. The HAPC model will produce biased estimates under many plausible scenarios (34). For a thorough overview, Bell and Jones (45) provided an extensive list of articles debating HAPC models. Conclusions drawn from this study rely on assumptions that are difficult or impossible to verify. Specifically, in some models, we assumed that cohort effects are a more plausible explanation for secular trends than are period effects. This assumption may be justified based on past research that suggests that predictors of later age grip strength tend to be present prior to middle age, suggesting that any specific period effect is likely to have a limited impact on current grip strength. However, from the data available, it is not possible to definitively disentangle cohort and period effects. This limitation applies to all APC modeling attempts. Beyond APC modeling, our data were excellent in terms of overall sample size but limited in the number of longitudinal observations (max = 4). Furthermore, the final wave of ELSA nurse data was limited, both in data and sample size, due to budgetary constraints. In addition, we have only examined data from a single, relatively homogeneous, sample, thus our substantive findings may not generalize beyond the setting in which the study was conducted (the United Kingdom in the early twenty-first century).

What To Do About Age, Period, and Cohort?

Despite the intractability of full APC models, the question they attempt to answer is an important one and one that researchers at times will need to answer. What should researchers do in these circumstances? Our first suggestion is to have a strong theory. In this case, the methods the researcher will use will flow from theory. If the researcher believes that cohort and period have random effects, then the HAPC model could be an appropriate model. If the researcher has specific causal mechanisms that they believe are important, then other methods, such as the mechanism-based approach to APC models, may be appropriate (49). If a researcher lacks concrete theoretical mechanisms and is unwilling to accept that period and cohort effects are merely random noise, then methods that examine the nonlinear aspects of the aging, period, and cohort trends are likely to be of interest. The nonlinear aspects of these trends can be identified using standard modeling techniques, and with a principled application of theory (eg, regarding the general direction that an effect is expected to take), these methods can help to illuminate such trends (46)). Our strongest recommendation is that researchers ensure that they fully understand and explain to their audience the assumptions that their APC model makes, as these assumptions can be quite opaque and can fundamentally alter the results that are produced.

Conclusions

While one can make compelling arguments for why age, period, and cohort should affect a foundational health measure like grip strength, mechanistic approaches will never be able to fully separate APC effects. This confounding means that we will always be left with some ambiguity in distinguishing age, period, and cohort effects. We have made a brief case for why we may favor the estimation of cohort effects to period effects in the case of grip strength, but either effect, should it exist, appears likely to be quite small. Age effects, on the other hand, are large and relatively consistent across different data analytic procedures. These statements emerge from a design that considers multiple methods for separating these potential effects and finds convergence across these methods to support the importance of an aging interpretation. Thus, if secular trends exist, they are likely to be dominated by age effects.

As the population ages, we expect declines in the population's average grip strength. The decline we observe due to age is statistically significant and moderate in size. It amounts to a loss of 0.40 kg of grip strength per year for older adults. Moreover, the decline is substantially steeper for men than women. This decline should lead us to expect marked changes in population-level grip strength, and in turn, higher rates of disability and a lowering of general health, insofar as grip strength remains an accurate measure of general health. Where we did occasionally find statistically significant period or cohort effects, for practical purposes, they were small (and consistently so in models that controlled for age). Small effects can be important, but because the age effect was orders of magnitude larger than even our largest estimated period or cohort effect (in models accounting for age), it appears the process underlying the longitudinal changes in ELSA is related largely to aging.

Supplementary Material

Supplementary data are available at *The Journals of Gerontology, Series A: Biological Sciences and Medical Sciences* online.

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Conflict of Interest

None declared.

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Author Contributions

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