



Original research

Muscular strength across the life course: The tracking and trajectory patterns of muscular strength between childhood and mid-adulthood in an Australian cohort



Brooklyn J. Fraser^a, Leigh Blizzard^a, Marie-Jeanne Buscot^a, Michael D. Schmidt^b,
Terence Dwyer^{a,c,d,e}, Alison J. Venn^a, Costan G. Magnussen^{a,f,g,*}

^a Menzies Institute for Medical Research, University of Tasmania, Australia

^b Department of Kinesiology, University of Georgia, USA

^c George Institute for Global Health, Oxford Martin School and Nuffield Department of Obstetrics & Gynaecology, Oxford University, UK

^d Murdoch Children's Research Institute, Australia

^e Faculty of Medicine, Dentistry and Health Sciences, University of Melbourne, Australia

^f Research Centre of Applied and Preventive Cardiovascular Medicine, University of Turku, Finland

^g Centre for Population Health Research, University of Turku and Turku University Hospital, Finland

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ABSTRACT

Objectives: Low muscular strength is a risk factor for current and future adverse health outcomes. However, whether levels of muscular strength persist, or track, and if there are distinct muscular strength trajectories across the life course is unclear. This study aimed to explore muscular strength trajectories between childhood and mid-adulthood.

Design: Prospective longitudinal study.

Methods: Childhood Determinants of Adult Health Study participants had their muscular strength (right and left handgrip, shoulder extension and flexion, and leg strength measured by hand-held, shoulder and leg-back dynamometers, and a combined strength score) assessed in childhood, young adulthood and mid-adulthood. The tracking of muscular strength was quantified between childhood and mid-adulthood ($n = 385$) and young- and mid-adulthood ($n = 822$). Muscular strength trajectory patterns were identified for participants who had their muscular strength assessed at least twice across the life course ($n = 1280$). **Results:** Levels of muscular strength were persistent between childhood and mid-adulthood and between young- and mid-adulthood, with the highest tracking correlations observed for the combined strength score (childhood to mid-adulthood: $r = 0.47, p < 0.001$; young- to mid-adulthood: $r = 0.72, p < 0.001$). Three trajectories of combined muscular strength were identified across the life course; participants maintained average, above average, or below average levels of combined muscular strength.

Conclusions: Weak children are likely to become weak adults in midlife unless strategies aimed at increasing muscular strength levels are introduced. Whether interventions aimed at increasing muscular strength could be implemented in childhood to help establish favourable muscular strength trajectories across the life course and in turn, better future health, warrant further attention.

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Practical implications

- Childhood muscular strength levels are important in predicting strength levels across the life course to mid-adulthood. Strength screening in childhood could identify individuals with low strength at risk of developing adverse health outcomes.

- Given the likely challenges of implementing population-wide screening of multiple strength measurements, grip strength is a feasible and reliable measure of overall strength that could be recommended as a screening tool.
- Interventions aimed at increasing muscular strength could be implemented in childhood to help establish favourable muscular strength trajectories across the life course.

* Corresponding author.

E-mail address: costan.magnussen@utas.edu.au (C.G. Magnussen).

1. Introduction

Muscular strength is a marker of current and future health. For adults, low muscular strength is associated with all-cause mortality.¹ In childhood, higher muscular strength is associated with lower adiposity and improved cardiovascular and bone health, and self-esteem.^{2,3} Health-benefits of childhood muscular strength extend into adulthood, with higher levels associated with decreased mortality⁴ and cardiometabolic disease.^{5,6} Furthermore, greater muscular strength in childhood, young- and mid-adulthood are equally associated with reduced odds of prediabetes in midlife.⁷ These findings highlight the importance of muscular strength across the life course, beginning in childhood. However, only 15.8% of Australian children meet muscle-strengthening guidelines.⁸ To explore if targeting childhood muscular strength could help improve future health, research quantifying how levels of muscular strength persist, or track, across the life course is required.

Levels of muscular strength track from childhood to adulthood.^{9–11} Findings from the Childhood Determinants of Adult Health (CDAH) Study showed that after a ~20-year follow-up, compared with children with high muscular strength, children with low muscular strength were 4.7 times more likely to have low muscular strength in young adulthood.¹² However, limited studies have explored the tracking of muscular strength between childhood and mid-adulthood. Quantifying the tracking of muscular strength to mid-adulthood will provide insight into the stability and predictive ability of muscular strength.¹³ These findings could promote childhood muscular strength as a screening tool to help identify individuals early in life at high risk of maintaining unfavourable levels of muscular strength into midlife. Once high-risk individuals are identified, their muscular strength trajectories could be altered. Describing muscular strength trajectories extends typical tracking analyses by identifying if there are meaningful subgroups of individuals who follow similar muscular strength pathways across the life course.¹⁴ However, before trajectories can be targeted, they must be better understood. It is currently unknown if distinct muscular strength trajectories are present between childhood and mid-adulthood in the general population.

In a large representative Australian cohort, this study examined the tracking of measures of muscular strength and describe trajectories of muscular strength between childhood and mid-adulthood.

2. Methods

As part of the Australian Schools Health and Fitness Survey (ASHFS), a nationally representative sample of 8498 Australian school children 7–15 years of age had their health and fitness assessed in 1985. Time and economic constraints meant that only a subset of children 9, 12 and 15 years of age had their muscular strength measured ($n=2808$). Participants were followed up as part of the CDAH Study and attended clinics in young adulthood (2004–06: 26–36 years of age) and mid-adulthood (2014–19: 36–49 years of age). At both adult follow-ups, muscular strength was remeasured. Participants who had at least one measure of muscular strength measured in childhood and mid-adulthood ($n=385$) and in young- and mid-adulthood ($n=822$) were included in tracking analyses. Participants who had their muscular strength assessed at least twice across the life course were included in trajectory analyses ($n=1280$). Women who were pregnant at the time of measurement were excluded. The State Directors General of Education approved the ASHFS and the Southern Tasmania Health and Medical Human Research Ethics Committee and the Tasmania Health and Medical Human Research Ethics Committee approved the follow-up studies. Consent was obtained from a parent and

assent obtained from the child at baseline and participants provided written informed consent at follow-up.

Muscular strength was assessed as maximum voluntary contractile force of the right and left grip, shoulder flexion and extension, and leg, using isometric dynamometers (Smedley's Dynamometer, TTM, Tokyo, Japan) in childhood, young- and mid-adulthood. Except for grip strength in childhood where only one attempt was allowed, all other measures of muscular strength were assessed twice, and the maximum attempt was included in analyses. Right and left grip was assessed as participants held a hand dynamometer with one hand, rested it on their opposite shoulder for stability, and gripped the dynamometer with maximum force. Shoulder flexion and extension was measured using a shoulder dynamometer. Participants held the dynamometer in front of their chest with both hands parallel to the ground and pushed (flexion) or pulled (extension) with maximum effort aiming to get their hands as close together or as far apart as possible. Leg strength was measured as participants stood flat-footed on a leg-back dynamometer and rested their back flat against a wall behind them. Looking forward, participants then held a bar with an overhand grip flat on the front of their thighs. While holding the bar, participants then bent their knees until an angle of 115° was reached. At this point, a research technician attached the bar to the dynamometer by a chain. While continuing to look forward and keeping their back straight, participants pulled the bar as far upwards as possible by sliding their body up the wall behind them using only their legs.

Body mass was measured to the nearest 0.5 kg using regularly calibrated scales in childhood and to the nearest 0.1 kg in adulthood using Heine scales (Heine, Dover, NH). Measures of muscular strength not attributable to body mass were created by regressing each muscular strength measure on body mass and using the residuals added to the grand mean.⁶ Each muscular strength measure was then age- and sex-standardised. A combined muscular strength score including all five measures of muscular strength was created by principal component analysis, where the first principal component of each of the five muscular strength measures was obtained (see Table S1 for factor loadings).⁶

All statistical analyses were performed using Stata (version 16.0, StataCorp, College Station, TX). Participant characteristics are stratified by life stage and are presented as mean (standard deviation).

The tracking of muscular strength between childhood and mid-adulthood and between young- and mid-adulthood was examined using Spearman's rank-order correlations. Correlations between measures of muscular strength in childhood and mid-adulthood were presented age- and sex-stratified and age- and sex-combined, whereas correlations between measures of muscular strength in young- and mid-adulthood were sex-stratified and sex-combined. Each correlation was adjusted for length of follow-up and baseline age and sex where appropriate.

Muscular strength tracking was also examined using stability analysis.¹² In the absence of health-related criterion-referenced physical fitness cut-points for Australian populations, muscular strength status at each time-point was defined by separating the combined muscular strength score into thirds. Log-multinomial regression models were used to examine the risk (relative risk [RR] and 95% confidence intervals [CI]) of a person maintaining their muscular strength status between childhood and mid-adulthood and between young- and mid-adulthood.¹⁵ For each model, high muscular strength at baseline was the referent group and high muscular strength at follow-up was the excluded outcome group. All effects were adjusted for baseline age, sex, and length of follow-up. Furthermore, muscular strength thirds at baseline and follow-up were cross-tabulated to provide a proportion of participants who maintained or changed their muscular strength status.

Adapting an approach by Seaman et al.,¹⁶ all correlation and stability tracking analyses included inverse probability weighting

with multiple imputation of incomplete baseline data to account for missing data at follow-up.

Trajectories of combined muscular strength between childhood and mid-adulthood were identified by group-based trajectory modelling (GBTM)¹⁴ using the Stata *traj* command.¹⁷ Participants with data on the combined muscular strength score (including each of the five individual age- and sex-standardised measures of muscular strength not attributable to body mass) at two or three time-points were included. GBTM predicted a trajectory and its form for each group, estimated the probability of group membership for each participant and used these probability values to allocate participants to the group for which they had the greatest probability of belonging. Trajectories were modelled using the censored normal distribution. The Bayesian information criteria (BIC) was used as the criterion for model selection. The four diagnostic criteria used to assess model adequacy were: 1) an average posterior probability value >0.7 for each group; 2) odds of correct classification for each group of >5.0; 3) similarity between each group's estimated probability and the proportion of participants assigned to that group based on the maximum posterior probability assignment rule; and 4) narrow confidence intervals for group membership probabilities highlighted by non-overlapping confidence intervals in trajectory figures.¹⁴

3. Results

Participant characteristics are presented in Table S2. On average, muscular strength increased between childhood and young adulthood and remained relatively similar between young- and mid-adulthood. Body mass increased with increasing age.

The average length of follow-up between childhood and mid-adulthood was 32.5 (1.2) years. Table 1 presents the Spearman's rank-order correlations for each measure of muscular strength between childhood and mid-adulthood. Right and left grip strength and the combined muscular strength score tracked the most. When examining the whole cohort, upper body strength measures tracked more for males than females and leg strength tracked more for females than males. This trend was consistent for age-stratified analyses, except for participants 15 years of age at baseline where the reverse was found. Generally, the highest tracking correlation coefficients were observed for those aged 15 years at baseline. Stability analyses showed that a child with low muscular strength was 3.17 times more likely to have low muscular strength in mid-adulthood, compared with a child with high muscular strength (Table 2). Cross tabulation of child and mid-adult muscular strength thirds showed 55.7% of participants remained in the lowest muscular strength third between childhood and mid-adulthood (Table S3).

The Spearman's rank-order correlations between measures of muscular strength in young- and mid-adulthood are presented in Table 1. The average length of follow-up was 12.5 (1.2) years. Muscular strength tracked well between these adult time-points, with the largest correlation coefficients observed for right and left grip strength and the combined muscular strength score. Although consistent for both sexes, measures tended to track more for females, with the exception of shoulder extension that tracked marginally more for males. Stability analyses showed that compared with having high muscular strength, a participant with low muscular strength in young adulthood was 9.63 times more likely to have low muscular strength in mid-adulthood (Table 2). Furthermore, 71.7% of participants had low muscular strength at each adult time-point compared with 4.1% of participants who had low muscular strength in young adulthood and high muscular strength in mid-adulthood (Table S4).

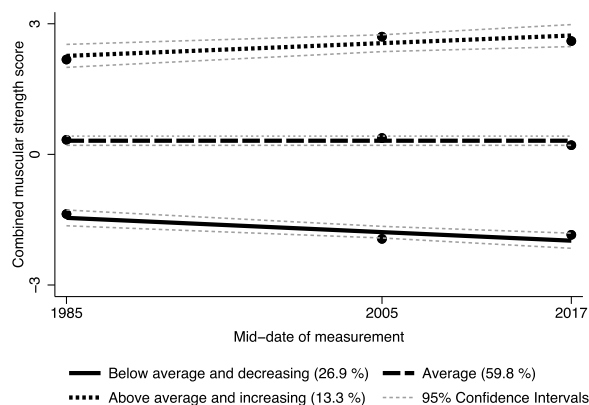


Fig. 1. Combined muscular strength score trajectory groups between childhood and mid-adulthood. The combined muscular strength score was created including each age- and sex-standardised measure of muscular strength (right and left grip strength, shoulder flexion and extension, and leg strength) not attributable to body mass. Dots represent observed mean combined muscular strength score values, small-dash, long-dash and solid black lines represent predicted combined muscular strength score values and grey dashed lines represent 95% confidence intervals.

Three trajectory groups of combined muscular strength were identified over a mean length of follow-up of 32.4 (1.3) years (Fig. 1). Figure S1 shows individual trajectories for each participant. Compared with those of similar age and sex in this cohort, participants' levels of muscular strength remained around average ($n = 785$, 59.8%), above average and increasing ($n = 156$, 13.3%) and below average and decreasing ($n = 339$, 26.9%). The average posterior probability for each group was >0.7 (range=0.87–0.89) and the odds of correct classification ranged from 5.6–43.4, exceeding the criteria of 5.0. Furthermore, the estimated probability and the proportion of participants assigned to each group based on the maximum posterior probability rule were similar. These statistics (Table S5) suggest that the trajectory model fitted these data well.

4. Discussion

We found that levels of upper, lower, and combined muscular strength remain relatively stable across the life course to mid-adulthood and that participants tended to maintain average, above average and increasing, or below average and decreasing levels of combined muscular strength between childhood and mid-adulthood.

Our study adds to the literature^{11,18,19} by showing that in an Australian cohort, muscular strength in young adulthood is a predictor of levels of muscular strength approximately 12 years later. Furthermore, we showed that ~72% of participants maintained a low muscular strength status during adulthood, highlighting the lack of intervention or difficulty in changing behaviour between young and mid-adulthood. This study also expands understanding of how muscular strength tracks between childhood and adulthood. Previous research is limited by examining data from relatively small cohorts including only one sex^{10,11} or having a follow-up period that did not extend into mid-adulthood.^{9,12} Our study, however, quantified the tracking of muscular strength over a follow-up period of up to 34-years in a cohort of both sexes. Results suggest that levels of muscular strength track between childhood and mid-adulthood in a pattern similar to how they track between childhood and young adulthood.^{9,12} The Trois-Rivières Growth and Development Study ($n = 191$, 10–12 years of age, follow-up period = 25 years)⁹ and the CDAH Study ($n = 623$, 9–15 years of age, follow-up period = 20 years)¹² both concluded that levels of muscular strength track between childhood and young adulthood (e.g. for grip strength and 12 years of age at baseline: females = 0.48–0.67;

Table 1
Spearman's rank-order correlation coefficients for tracking of measures of muscular strength between childhood and mid-adulthood and between young- and mid-adulthood.

	Right grip strength	Left grip strength	Shoulder flexion	Shoulder extension	Leg strength	Muscular strength score
Between childhood and mid-adulthood						
9 years of age						
Male	0.34**	0.57***	0.22	0.21	0.11	0.37**
Female	0.30*	0.27*	0.25*	-0.06	0.40***	0.40***
Combined	0.33***	0.41***	0.21*	0.06	0.28**	0.39***
12 years of age						
Male	0.47***	0.39**	0.09	0.13	0.27	0.48***
Female	0.28*	0.31**	0.22	0.35**	0.40***	0.36**
Combined	0.35***	0.34***	0.13	0.24**	0.33***	0.39***
15 years of age						
Male	0.39**	0.57***	0.35*	0.41**	0.51***	0.62***
Female	0.51***	0.69***	0.20	0.26*	0.27*	0.68***
Combined	0.45***	0.62***	0.27**	0.32**	0.36***	0.66***
Participants of all ages						
Male	0.42***	0.50***	0.24**	0.22**	0.26***	0.48***
Female	0.35***	0.36***	0.22**	0.15*	0.33***	0.44***
Combined	0.40***	0.44***	0.23***	0.19***	0.31***	0.47***
Between young- and mid-adulthood						
Participants of all ages						
Male	0.60***	0.64***	0.50***	0.62***	0.55***	0.66***
Female	0.69***	0.72***	0.52***	0.50***	0.57***	0.77***
Combined	0.64***	0.68***	0.51***	0.57***	0.56***	0.72***

All correlation coefficients are adjusted for length of follow-up. Sex and baseline age are included as adjustment factors where appropriate.

* $p < 0.05$
 ** $p \leq 0.01$.
 *** $p \leq 0.001$.

Table 2
Log multinomial regression between muscular strength thirds in childhood and mid-adulthood and between muscular strength thirds in young- and mid-adulthood*.

	Muscular strength in mid-adulthood†			
	Middle third		Lowest third	
	RR	95% CI	RR	95% CI
Muscular strength third in childhood				
Highest third	1	REF	1	REF
Middle third	1.31	0.86–2.01	2.10	1.24–3.57
Lowest third	1.30	0.82–2.06	3.21	1.91–5.38
P_{trend}		0.27		<0.001
Muscular strength third in young adulthood				
Highest third	1	REF	1	REF
Middle third	1.74	1.36–2.22	2.88	1.65–5.04
Lowest third	0.76	0.56–1.05	9.63	5.81–15.95
P_{trend}		0.09		<0.001

* All associations are adjusted for baseline age, sex, and length of follow-up.
 † The highest muscular strength third in mid-adulthood was the excluded outcome group.
 Abbreviations: RR, relative risk; CI, confidence intervals.

males = 0.30–0.32).^{9,12} Consistent trends between these findings and our own include grip strength and the combined muscular strength score having the highest tracking correlations and generally, the tracking of muscular strength between childhood and adulthood increased with increasing baseline age.^{9,12} However, when comparing the two CDAH studies, a few differences were observed. We previously showed that between childhood and young adulthood, upper body strength measures tracked more for females compared with males,¹² whereas the reverse was true between childhood and mid-adulthood in this current study. Furthermore, the tracking of muscular strength between childhood and mid-adulthood was generally higher than the tracking between childhood and young adulthood.¹² Collectively, these results suggest that childhood muscular strength predicts levels of muscular strength in young- and mid-adulthood. These findings highlight childhood as a potentially key time to promote increased muscular strength to help encourage favourable levels into later life, although continued efforts to increase muscular strength at each life stage is likely to be important. Research is required to explore whether interventions aimed at increasing muscular strength could be implemented in childhood to help

establish favourable muscular strength trajectories across the life course.

Studies that have identified muscular strength trajectories have been limited by examining only one life stage (i.e. only in adulthood^{20,21}) or by using combined data from different cohorts.²² However, no previous study has identified muscular strength trajectories across the life course using repeated measures of muscular strength in the one national cohort. Trajectories of the combined muscular strength score were identified. The combined score best represents overall muscular strength and was created including each age- and sex-standardised measure of muscular strength not attributable to body mass. Therefore, the identified trajectories highlight the stability of levels of muscular strength across the life course to mid-adulthood after accounting for age, sex, and body mass at each time-point. The pattern of these trajectories confirms the tracking of muscular strength between childhood and mid-adulthood and suggests that levels of muscular strength in childhood are important in establishing how levels of muscular strength are likely to be maintained across the life course. We found that participants generally maintained average, above average, or below average combined muscular strength between childhood

and mid-adulthood. These findings reinforce the importance of promoting muscular strength to children at all levels of muscular strength to help give them the best opportunity to be part of favourable muscular strength trajectories into adulthood.

Low muscular strength is a risk factor for future adverse health,²³ although it is not muscular strength at only one life stage that has a meaningful impact on these outcomes. For example, greater muscular strength in childhood, young- and mid-adulthood is equally associated with reduced odds of prediabetes or type 2 diabetes in midlife.⁷ Being able to identify a person at risk by measuring their muscular strength 30-years before disease onset is significant. The results of our tracking and trajectory analyses suggest that childhood muscular strength could be used to help identify those at high risk of maintaining low levels of muscular strength into adulthood and who are potentially at risk of developing adverse health outcomes. Given the likely challenges of implementing population wide screening of multiple strength measurements, grip strength is a feasible measure of overall strength that could be recommended as a screening tool. High-risk individuals could then be targeted with strategies aimed at increasing their level of muscular strength in childhood to benefit their long-term health and fitness. Childhood muscular strength could be improved directly through resistance training,^{24,25} including activities performed in a school-based setting,²⁶ or indirectly through targeting correlates of muscular strength including increased cardiorespiratory fitness and speed capability.²⁷ However, it is important that discussions regarding ways to increase muscular strength and promote favourable muscular strength trajectories consider both environmental and genetic factors, given both influence muscular strength.²⁸ Genetic factors may predispose individuals to a certain muscular strength trajectory or influence the way muscular strength levels can be increased, or are able to track, with time. Furthermore, less than 16% of children (15–17 years) and 25% of adults in Australia meet muscle-strengthening guidelines.⁸ Consistently low participation rates may hinder one's ability to build muscular strength across the life course. To better promote favourable muscular strength trajectories, research is required to explore why levels of muscular strength track well over time, including identifying the role genetics play and exploring barriers and facilitators to participation.

Potential limitations include loss to follow-up. Higher tracking was observed in this study between childhood and mid-adulthood than was presented previously between childhood and young adulthood.¹² Loss to follow-up could have influenced the strength of associations, with a different, more fit, and healthy, subset of participants attending clinics in mid-adulthood. However, our analyses included inverse probability weighting to account for missingness and reduce the likelihood of bias.¹⁶ Furthermore, in the absence of health-related criterion-referenced fitness cut-points in Australian children, our stability tracking analyses were based on strength categories relative to other study participants. Therefore, it is unclear how children with 'low' strength could be identified. Future research should establish fitness cut-points in Australian children linked with future adverse health outcomes. Study strengths include having muscular strength data measured on a national cohort at three life stages across a follow-up period of 34-years. Lastly, field-based measures used to assess muscular strength in this study are reliable and valid²⁹ and correlate well with gold-standard measures of muscular strength.³⁰

5. Conclusion

In conclusion, weak children are likely to become weak adults unless strategies aimed at increasing muscular strength levels are introduced. Whether interventions aimed at increasing muscu-

lar strength could be implemented in childhood to help establish favourable muscular strength trajectories across the life course and in turn, better future health, warrant further attention.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <https://doi.org/10.1016/j.jsams.2021.01.011>.

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