

Longitudinal Links Between Muscular Fitness, Physical Activity, Body Composition, and Sports Club Participation Across Childhood and Adulthood in Germany

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Longitudinal Links Between Muscular Fitness,
Physical Activity, Body Composition, and Sports
Club Participation Across Childhood and
Adulthood in Germany

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Abstract

Purpose: Muscular fitness represents a central component of physical fitness, associated with lower adiposity, better cardiometabolic and psychosocial health, and reduced mortality risk. It tracks from childhood into adulthood and is shaped by behavioral and physiological factors. This study investigated how physical activity, body composition, and sports club participation contribute to muscular fitness development from childhood to adulthood in a large national sample.

Methods: Longitudinal data from participants aged 4–31 years from the MoMo Study (2003–2017) were analyzed. Muscular fitness, physical activity, body fat percentage, waist-to-height ratio, and sports club participation were assessed using validated tests, questionnaires, and bioelectrical impedance analysis. Directional associations were examined using cross-lagged panel models. **Results:** The analysis showed small to large autoregressive effects across all variables ($\beta = 0.096\text{--}0.957$). Higher physical activity predicted higher subsequent Muscular fitness and performance ($\beta = 0.026\text{--}0.210$), while higher body fat percentage predicted lower later Muscular fitness and performance ($\beta = -0.051$ to -0.297). Sports club participation was also associated with higher subsequent Muscular fitness and performance ($\beta = 0.027\text{--}0.185$). Associations from muscular fitness to later physical activity, body composition, and sports club participation were weaker and less consistent. **Conclusion:** Muscular fitness and body composition showed high stability from childhood to early adulthood. Cross-lagged analyses indicate body fat percentage exerts stronger influences on Muscular fitness development than activity indicators. The results demonstrate that activity indicators and body fat percentage drive long-term fitness development, underscoring the need for early interventions to prevent persistent low muscular fitness and unfavorable body composition.

Keywords: longitudinal associations, Muscular Fitness, children and adolescents, anthropometries, physical activity

1 Introduction

Internationally, the term Muscular fitness is increasingly used as a comprehensive construct that integrates multiple aspects of muscular performance. Building on the framework by Caspersen et al. (1985) [1], Muscular fitness brings together three key components of physical fitness: muscular strength, the capacity of a muscle or muscle group to exert force; muscular endurance, the ability to perform repeated contractions or maintain a contraction over an extended period under submaximal load; and power, which describes the ability to generate force rapidly during dynamic movements and thereby reflects the rate of performing work [2, 3]. By combining these dimensions, Muscular fitness provides an integrated measure of muscle function and it is increasingly recognized as a central determinant of overall physical fitness and health. In Germany, physical fitness is commonly conceptualized according to the model by Bös

(1987) [4, 5], which distinguishes four main dimensions: endurance, strength, speed, and coordination, with flexibility as an additional passive energy transfer system. This framework has proven especially suitable for evaluating physical fitness in children and adolescents [5]. Each of the main dimensions can be further differentiated; for example, strength includes muscular endurance, maximal strength, and speed strength [5]. Given the strong conceptual overlap between this definition of strength and the internationally established construct of Muscular fitness, the two terms are used synonymously in the present study.

Beyond its conceptual importance, Muscular fitness is widely recognized as a key indicator of health with significant implications for both present well-being and future disease risk [3, 6–8]. Furthermore, previous studies indicate that low Muscular fitness is linked to a higher risk of premature mortality [9, 10]. In youth, higher Muscular fitness is associated with lower levels of adiposity, improved cardiovascular and skeletal health, as well as enhanced psychosocial outcomes such as self-perception and self-esteem [3, 6]. Additionally, Muscular fitness is positively associated with better health-related quality of life in children and adolescents [11, 12]. Conversely, lower Muscular fitness in children and adolescents has been linked to higher odds of reporting poorer self-rated health [13, 14]. Greater muscle strength also contributes to the prevention of cardiovascular diseases and is inversely related to age-related increases in weight and adiposity [2]. Longitudinal evidence further suggests that improvements in Muscular fitness can mitigate adiposity accumulation throughout childhood and adolescence, independent of sex-specific growth patterns [15]. Reflecting this evidence, international guidelines such as those issued by the World Health Organization emphasize the inclusion of muscle-strengthening activities as an essential component of physical activity to support overall health [16].

Evidence also indicates that Muscular fitness tracks over time, linking early-life levels to adult outcomes. Longitudinal studies show that Muscular fitness measures are

139 relatively stable through childhood and into adulthood [8, 17–20], with the strongest
140 correlations observed for a combined Muscular Fitness score [8, 17, 19], grip strength,
141 Standing long jump performance [19], or flexed arm hang [20]. Children and adoles-
142 cents with low Muscular fitness are at increased risk of remaining in the lowest fitness
143 categories as adults [18, 19]. Overall, muscular strength and endurance demonstrate
144 moderate tracking, somewhat stronger in women than in men and more pronounced
145 when assessed from adolescence compared to childhood [21]. Furthermore, children
146 living in urban areas and those continuously participating in sports clubs show greater
147 levels and improvements in muscular strength than children living in rural areas and
148 those non-participating in sports clubs [22, 23]. Additionally, children with higher
149 physical activity showed better performances in strength measures [24, 25]. Collec-
150 tively, these findings underscore the importance of promoting Muscular fitness from an
151 early age, given its persistence across the life course, its strong association with health
152 outcomes, and the particularly positive role of continuous sports club participation.

153 Previous studies have examined the roles of physical activity, body composition,
154 and sports club participation, but most relied on regional samples, short follow-up
155 periods, or addressed only one aspect at a time. As a result, the long-term development
156 of Muscular fitness, despite its importance for health and its moderate tracking from
157 childhood into adulthood, remains insufficiently understood. To address this gap, the
158 present study analyzes how physical activity, body composition, and sports club par-
159 ticipation are each associated with the longitudinal development of Muscular fitness
160 in a large german-wide sample spanning from childhood to adulthood.

162 2 Methods

163 2.1 Study design and sample

164 Data were obtained from the German Motorik-Modul (MoMo) Longitudinal Study,
165 which investigated physical fitness and physical activity in children and adolescents

aged 4 to 17 years in Germany [26, 27]. The MoMo study is conducted as part of the German Health Interview and Examination Survey for Children and Adolescents (KiGGS) [28], the first nationwide health monitoring system for children and adolescents in Germany, coordinated by the Robert Koch Institute. KiGGS was launched in 2003 and included the MoMo study as one of its five substudies. Participants were randomly selected from population registries in 167 German cities and municipalities [28, 29]. Children and adolescents were first enrolled in KiGGS and subsequently invited to take part in the MoMo study.

The MoMo Baseline Measurement Wave (T1) was conducted between 2003 and 2006, followed by three subsequent Measurement Waves: Wave 1 (T2: 2009–2012), Wave 2 (T3: 2014–2017), and Wave 3 (T4: 2018–2022). At each wave, a representative stratified cross-sectional sample of participants aged 4–17 years was drawn. In addition, individuals from the T1 baseline cohort were re-assessed longitudinally, resulting in a cohort-sequential study design that combined new cross-sectional samples with longitudinal follow-up data [26, 30]. Participants enrolled at T1 could miss one follow-up wave (e.g., T2 or T3) and still be eligible for later assessments. Furthermore, new participants were allowed to enter the longitudinal arm at T2.

Families received individual invitations to attend nearby study centers, where trained test administrators carried out standardized physical fitness tests and questionnaires (for details see [31]). Study centers were chosen to minimize travel distances and facilitate participation. Parents provided written informed consent for the participation of minors. For participants younger than 16 years, the presence of a legal guardian during the assessment was mandatory.

For the present analyses, we used longitudinal data from participants who completed physical fitness testing at least twice between T1 and T3 (i.e., T1–T2–T3, T1–T2, T1–T3, or T2–T3).

2.2 Measures

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2.2.1 Muscular fitness

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In the MoMo study physical fitness was assessed using the 12-item MoMo test profile [30, 31], developed based on the approach proposed by Bös (1987) [4] and validated by Oberger and colleagues [32]. For the present analyses, three test items measuring Muscular fitness (physical strength) were included:

- Standing long jump – maximum distance achieved (in cm) from two valid standing trials.
- Push-ups – total number of repetitions completed within 40 seconds (one trial).
- Sit-ups – total number of repetitions completed within 40 seconds (one trial).

It should be noted that the Sit-up test was introduced at the second measurement wave (T2) to further optimize the MoMo test profile. In addition, Push-ups and Sit-ups were administered only to participants aged six years and older for developmental appropriateness. The remaining fitness tests were conducted from the age of four years.

2.2.2 Physical activity

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The MoMo Physical Activity Questionnaire (MoMo-PAQ), which assesses different types and settings of physical activity, as well as overall activity levels, was used to measure self-reported PA of all participants [33]. For younger participants, the questionnaire was completed with the support of parents or legal guardians, under the supervision of a trained test instructor. The level of parental involvement depended on the child’s reading and writing abilities. Participants reported the minutes per week and the number of months per year they engaged in curricular, extracurricular, club-based, and unorganized sports activities. For each club-based and unorganized activity, weekly minutes were adjusted for seasonal participation by multiplying them with a monthly activity factor (months active divided by 12) [34]. Curricular and

extracurricular activities were corrected for school holidays using a standard adjustment factor of 8.5 divided by 12. All activity-specific minutes were then summed to form the weekly Physical Activity Index [34].

2.2.3 Body composition

Body composition was assessed using two indicators: waist-to-height ratio and body fat percentage. Waist-to-height ratio was calculated as waist circumference divided by body height. Waist-to-height ratios below 0.3 were removed as they were deemed implausible [35]. Body fat percentage was determined via tetrapolar bioelectrical impedance analysis (BIA) using a BIA 2000-S analyzer (Data Input, Frankfurt, Germany) [36]. For the measurement, participants rested in a quiet supine position for at least three minutes before resistance (R) and reactance (Xc) were recorded between the right wrist and ankle via surface electrodes. Measurements were taken over a 15-second interval until values stabilized, and the final reading was documented [36]. Total body fat (kg) was calculated with formulas provided in the NutriPlus software package (Data Input, Frankfurt, Germany) [37], and body fat percentage was derived as the ratio of total fat mass to total body weight. Body fat percentages below 5% were removed as they were deemed implausible [38].

2.2.4 Sports club participation

As part of the MoMo-PAQ participants were asked at each measurement if they are currently a member of a sports club [39]. The following answers were possible:

- No, I have never been a member of a sports club.
- No, I am not currently a member but I was previously a member.
- Yes, I am currently a member of a sports club/several sports clubs.

323 For this analyses the answers were dichotomized into "Yes, I am currently a member
324 of a sports club/several sports clubs" and "No, I am not currently a member of a
325 sports club/several sports clubs".
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329 2.3 Statistical analyses

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331 To assess whether the measurement structure of the dependent variables was stable
332 across time, we conducted longitudinal tests of measurement invariance [40–42]. A
333 series of confirmatory factor analyses (CFA) with progressively stricter equality con-
334 straints were estimated [43, 44]. The indicators (Standing long jump attempt one and
335 two, Sit-ups, and Push-ups) were modeled as indicators of a latent variable repre-
336 senting Muscular fitness. We examined configural, weak, strong, and strict invariance
337 sequentially, allowing the residual covariances between the two Standing long jump
338 measures to vary freely in all models. Missing data were handled model immanent
339 using full information maximum likelihood estimation [45].
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342 Given the longitudinal but observational nature of our data, we specified different
343 Cross-Lagged Panel Models (CLPM) to get closer to the estimation of causal effects.
344 Since we had in total three waves, we specified CLPM with lag-1 (CLPM) and lag-
345 2 (CL2PM) [46]. In both versions, we focused on the association between each of
346 the Muscular fitness measures (Standing long jump, Push-ups, Sit-ups, and Muscular
347 fitness score) and physical activity, the waist-to-height ratio, the body fat percentage,
348 and sports club participation; resulting in a total of 24 models. To give an example
349 for a CLPM, we focus on the association between Standing long jump and physical
350 activity across the three measurement time points: The paths from 1) physical activity
351 (T1) to Standing long jump (T2) and vice versa as well as the paths from 2) physical
352 activity (T2) to Standing long jump (T3) and vice versa are the so-called cross-lagged
353 paths (see Figure 1 A). The respective cross-lagged effects were interpreted based on
354 the recommendations by Orth et al. (2024) [47] with $\beta \geq 0.03$ as small, $\beta \geq 0.07$ as
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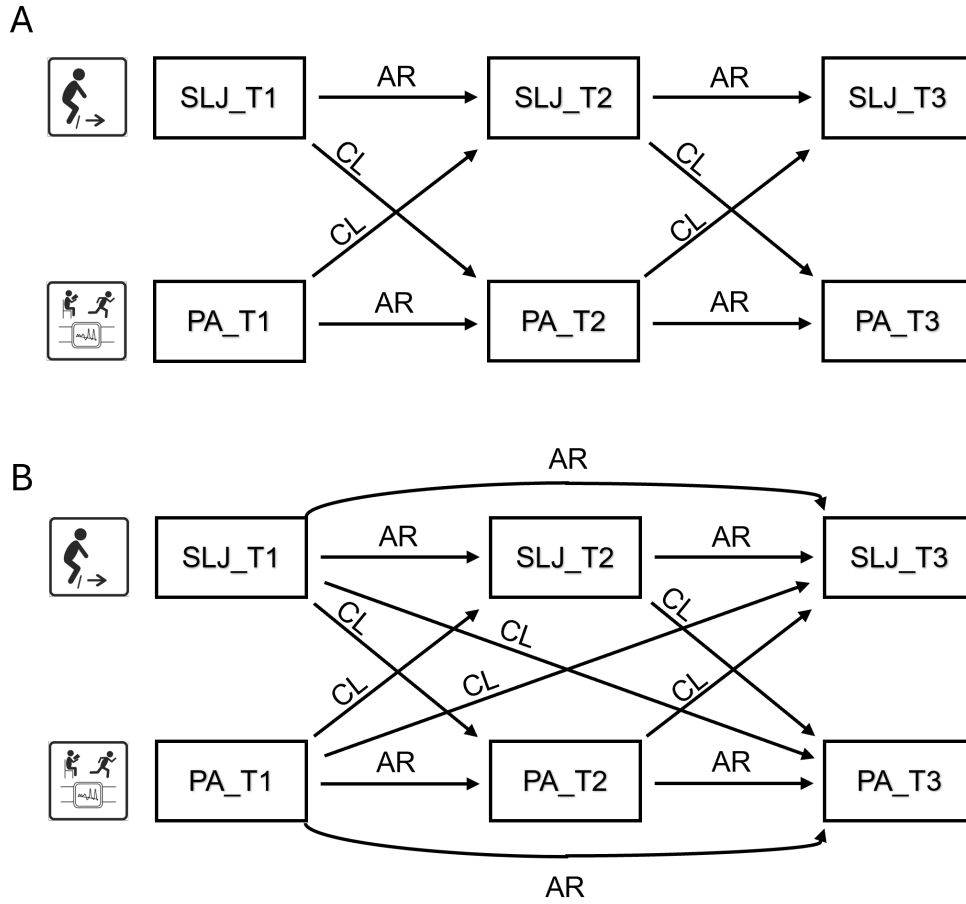


Fig. 1 Example of a Cross-Lagged Panel Model with lag-1 (A) and a Cross-Lagged Panel Model with lag-2 (B) for the Standing long jump and physical activity. SLJ Standing long jump; PA Physical activity; T1 Baseline Measurement Wave; T2 Measurement Wave 1; T3 Measurement Wave 2; AR Auto-regressive path; CL Cross-lagged path

medium, and $\beta \geq 0.12$ as large. The so-called auto-regressive paths demonstrate the stability of, for example Standing long jump or physical activity, over time (see Figure 1 A). These effects were interpreted as small for $\beta \geq 0.2$, medium for $\beta \geq 0.5$, and large for $\beta \geq 0.8$ based on the recommendations by Ferguson (2009) [48]. In the CL2PM additional autoregressive and cross-lagged paths from T1 to T3 were estimated (see Figure 1 B).

An overview of all specified models is depicted in Table 1. Model fit for the measurement invariance models was evaluated using multiple fit indices, including the Comparative Fit Index (CFI), Tucker–Lewis Index (TLI), Root Mean Square Error of Approximation (RMSEA), Standardized Root Mean Square Residual (SRMR), and the chi-square test (χ^2) with associated p-values. Evaluation was based on conventional benchmark criteria [49, 50]. All analyses were run using functions of the lavaan package [51] in R (Version 4.5.1) [52].

Table 1 Conducted Cross-Lagged Panel Models

Model	Predictors	Standing long jump	Push-ups	Sit-ups	Muscular fitness
CLPM	Physical activity	x	x	x	x
	Waist-to-height ratio	x	x	x	x
	Body fat percentage	x	x	x	x
	Sports club participation	x	x	x	x
CL2PM	Physical activity	x	x	-	-
	Waist-to-height ratio	x	x	-	-
	Body fat percentage	x	x	-	-
	Sports club participation	x	x	-	-

CLPM Cross-Lagged Panel Model with lag-1; CL2PM Cross-Lagged Panel Model with lag-2; X indicate that the model was specified; - indicate that the model was not specified due to unavailable data

3 Results

The study sample (Table 2) of this analysis included data from 3100 participants at T1, 3723 participants at T2, and 2616 participants at T3. At T1 and T2 roughly 48% of participants were male and 52% female, while at T3 nearly 46% were male and 54% were female. At T1 the participants were on average 9.48 years and ranged between 4 and 17 years. At T3 the participants were then on average 18 years old and ranged between 11 and 31 years.

Table 2 Study sample characteristics

Variables		T1	T2	T3
Sex	Overall [N]	3100	3723	2616
	Male [N]	1497	1788	1199
	Female [N]	1603	1935	1417
Age	Mean ($\pm SD$) [Years]	9.48 (3.93)	14.38 (4.55)	18.58 (4.61)
	Min [Years]	4.00	6.35	11.18
	Max [Years]	17.97	26.02	31.73
Standing long jump	Sample size [N]	3082	2869	1875
	Mean ($\pm SD$) [cm]	130.74 (37.76)	158.74 (33.71)	171.26 (34.23)
	Min [cm]	29.00	65.00	54.00
Push-ups	Max [cm]	270.00	282.00	281.00
	Sample size [N]	2330	2851	1857
	Mean ($\pm SD$) [N]	11.60 (3.85)	13.39 (4.00)	14.32 (4.11)
Sit-ups	Min [N]	0.00	0.00	0.00
	Max [N]	27.00	33.00	28.00
	Sample size [N]	-	2857	1875
Muscular fitness	Mean ($\pm SD$) [N]	-	20.91 (6.55)	21.24 (5.82)
	Min [N]	-	0.00	0.00
	Max [N]	-	50.00	40.00
Physical activity	Sample size [N]	-	3123	2349
	Mean ($\pm SD$)	-	0.01 (0.89)	0.35 (0.86)
	Min	-	-2.90	-3.16
Body fat percentage	Max	-	3.29	3.21
	Sample size [N]	3100	3723	2616
	Mean ($\pm SD$)	229.33 (176.79)	269.02 (202.05)	240.61 (214.59)
Waist-to-height ratio	[min/week]	0.00	0.00	0.00
	Min [min/week]	1488.75	2150.62	1727.29
	Max [min/week]	3045	2758	1600
Sports club participation	Sample size [N]	1876 (7.10)	21.96 (7.03)	23.57 (7.93)
	Mean ($\pm SD$) [%]	5.40	5.00	5.21
	Min [%]	56.30	54.72	52.02
Sports club participation	Max [%]	1052	2882	1873
	Sample size [N]	0.42 (0.04)	0.43 (0.05)	0.44 (0.05)
	Mean ($\pm SD$)	0.33	0.22	0.32
Sports club participation	Min	0.76	0.79	0.75
	Max	3082	3569	2589
	Sample size [N]	1818	2226	1343
Sports club participation	Yes [N]	1264	1424	1246
	No [N]			

T1 Baseline Measurement Wave; T2 Measurement Wave 1; T3 Measurement Wave 2; N Number of measurements; SD Standard deviation; Min Minimum; Max Maximum

3.1 Measurement invariance

The configural invariance model (Table 3) showed an acceptable overall fit to the data ($\chi^2 = 685.791$, $df = 18$, $p < .001$; RMSEA = 0.106; SRMR = 0.077; CFI = 0.961; TLI = 0.939). In line with conventional benchmarks [49, 50], these indices suggest that the basic factor structure of the latent Muscular fitness variable was adequately represented over time. Constraining the factor loadings to equality over time (weak invariance model; $\chi^2 = 726.839$, $df = 20$, $p < .001$; RMSEA = 0.103; SRMR = 0.089;

CFI = 0.959; TLI = 0.942) yielded only minor changes in model fit, indicating that the strength of the relations between indicators and the latent construct remained stable. The strong invariance model ($\chi^2 = 873.839$, $df = 23$, $p < .001$; RMSEA = 0.106; SRMR = 0.089; CFI = 0.950; TLI = 0.940) also produced comparable fit indices, suggesting that constraining the intercepts did not substantially deteriorate model fit. Finally, the strict invariance model ($\chi^2 = 911.164$, $df = 27$, $p < .001$; RMSEA = 0.099; SRMR = 0.092; CFI = 0.948; TLI = 0.947) demonstrated similarly acceptable fit values, supporting the assumption of longitudinal measurement invariance. Hence, the use of a single latent factor score to represent Muscular fitness across time points was justified.

Table 3 Model fits of the longitudinal measurement invariance

Model	CFI	TLI	RMSEA	SRMR	χ^2	Df	p-value
Configural	0.961	0.939	0.106	0.077	685.791	18	< .001
Weak	0.959	0.942	0.103	0.089	726.839	20	< .001
Strong	0.950	0.940	0.106	0.089	873.839	23	< .001
Strict	0.948	0.947	0.099	0.092	911.164	27	< .001

CFI Comparative Fit Index; TLI Tucker-Lewis Index; RMSEA Root Mean Square Error of Approximation; SRMR Standardised Root Mean Square Residual; χ^2 Chi-squared; Df Degree of freedom

3.2 Cross-Lagged Panel analysis

The CLPMs showed that overall Muscular fitness levels ($\beta = 0.944$ to 0.957 ; $p < .05$) and the performance levels of the three Muscular fitness measures ($\beta = 0.342$ to 0.903 ; $p < .05$) exhibited significant autoregressive effects across all measurement points (Figure 2). Furthermore, significant autoregressive effects across all measurement points were found for physical activity ($\beta = 0.251$ to 0.448 ; $p < .05$), body fat percentage ($\beta = 0.582$ to 0.649 ; $p < .05$), waist-to-height ratio ($\beta = 0.639$ to 0.725 ; $p < .05$), and sports club participation ($\beta = 0.339$ to 0.406 ; $p < .05$).

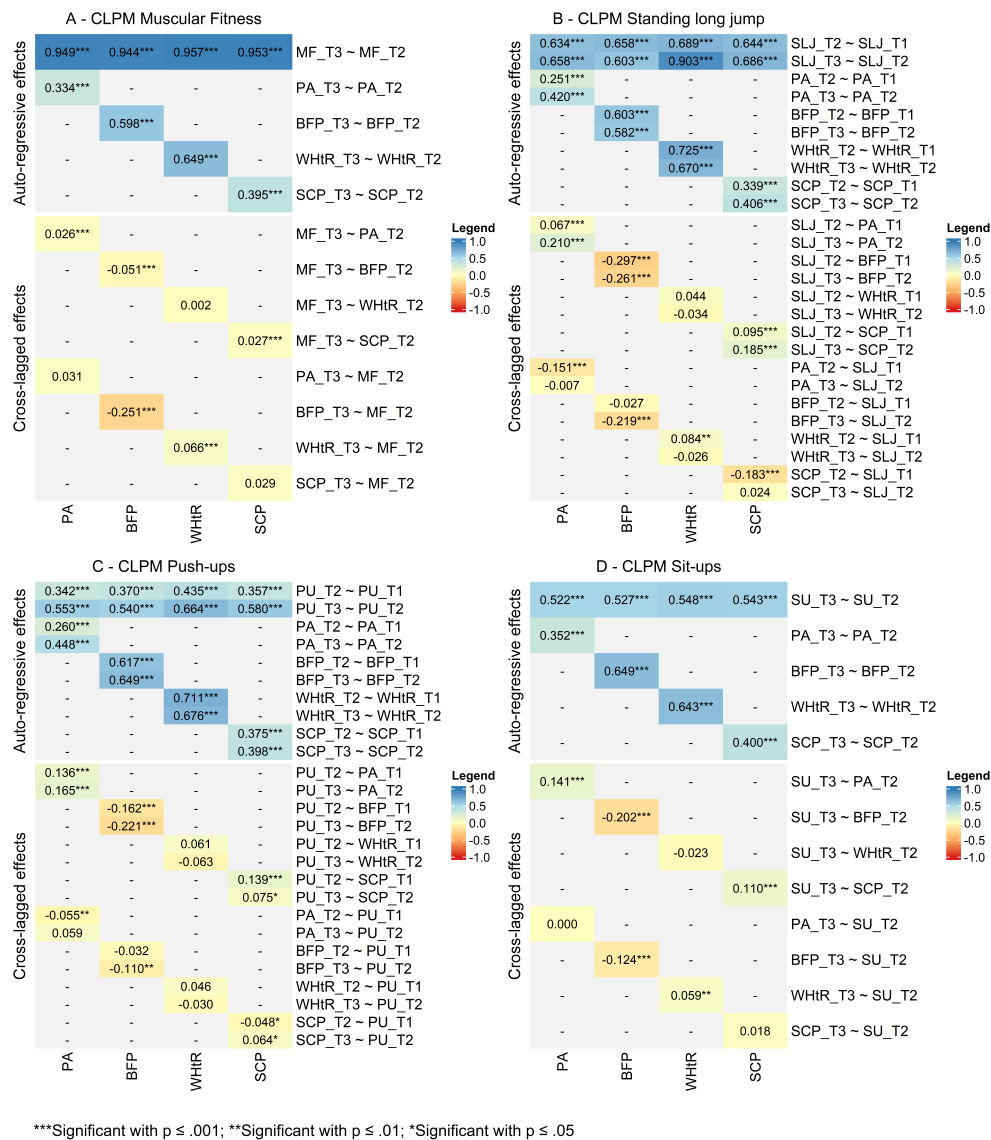


Fig. 2 Results of the Cross-Lagged Panel Models with lag-1. CLPM Cross-Lagged Panel Model; SLJ Standing long jump; PU Push-ups; SU - Sit-ups; MF Muscular fitness; T1 Baseline Measurement Wave; T2 Measurement Wave 1; T3 Measurement Wave 2; PA Physical activity; BFP Body fat percentage; WHtR Waist-to-height ratio; SCP Sports club participation

The cross-lagged paths revealed that Muscular fitness as well as the performance levels of the Standing long jump, Push-ups, and Sit-ups higher are positively influenced

599 by higher levels of physical activity ($\beta = 0.026$ to 0.210 ; $p < .05$), lower body fat
 600 percentage ($\beta = -0.051$ to -0.297 ; $p < .05$), and sports club participation ($\beta = 0.027$ to
 601 0.185 ; $p < .05$) at subsequent measurement points. Higher performance levels in the
 602 Standing long jump ($\beta = -0.151$; $p < .05$) and Push-ups ($\beta = -0.055$; $p < .05$) at T1
 603 negatively affected physical activity levels at T2. Moreover, higher Muscular fitness
 604 as well as the performance levels negatively impacted the body fat percentage from
 605 T2 to T3 ($\beta = -0.109$ to -0.247 ; $p < .05$). Further, higher Muscular fitness levels (β
 606 $= 0.066$; $p < .05$) and higher performances in Sit-ups ($\beta = 0.059$; $p < .05$) impacted
 607 the waist-to-height ratio from T2 to T3, while higher performance in the Standing
 608 long jump ($\beta = 0.084$; $p < .05$) had an influence from T1 to T2. Additionally, sports
 609 club participation was influenced by Standing long jump performance from T1 to T2 ($\beta = -0.183$; $p < .05$) and by Push-up performance from T1 to T2 ($\beta = -0.048$;
 610 $p < .05$), as well as from T2 to T3 ($\beta = 0.064$; $p < .05$). An overview of all path
 611 models for the conducted CLPMs are depicted in the supplement (see Additional file
 612 1; Supplementary Figures 1-16).
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614 The CL2PMs (Figure 3) showed that performance levels in the Standing long jump
 615 had significant autoregressive effects from T1 to T2 ($\beta = 0.654$ to 0.692 ; $p < .05$) and
 616 from T2 to T3 ($\beta = 0.341$ to 0.868 ; $p < .05$). For the Push-ups, positive effects were
 617 found from T1 to T2 ($\beta = 0.382$ to 0.455 ; $p < .05$), from T2 to T3 ($\beta = 0.407$ to 0.544 ;
 618 $p < .05$), and from T1 to T3 ($\beta = 0.095$ to 0.177 ; $p < .05$). Additionally, significant
 619 autoregressive effects across all measurement points were observed for physical activity
 620 ($\beta = 0.103$ to 0.376 ; $p < .05$), body fat percentage ($\beta = 0.222$ to 0.612 ; $p < .05$), and
 621 sports club participation ($\beta = 0.096$ to 0.378 ; $p < .05$). For the waist-to-height ratio,
 622 significant autoregressive effects were found from T1 to T2 ($\beta = 0.659$ to 0.668 ; $p <$
 623 $.05$) and from T2 to T3 ($\beta = 0.689$ to 0.701 ; $p < .05$).
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625 The cross-lagged paths revealed that higher levels of physical activity positively
 626 influenced performance levels in both the Standing long jump and Push-ups from T1
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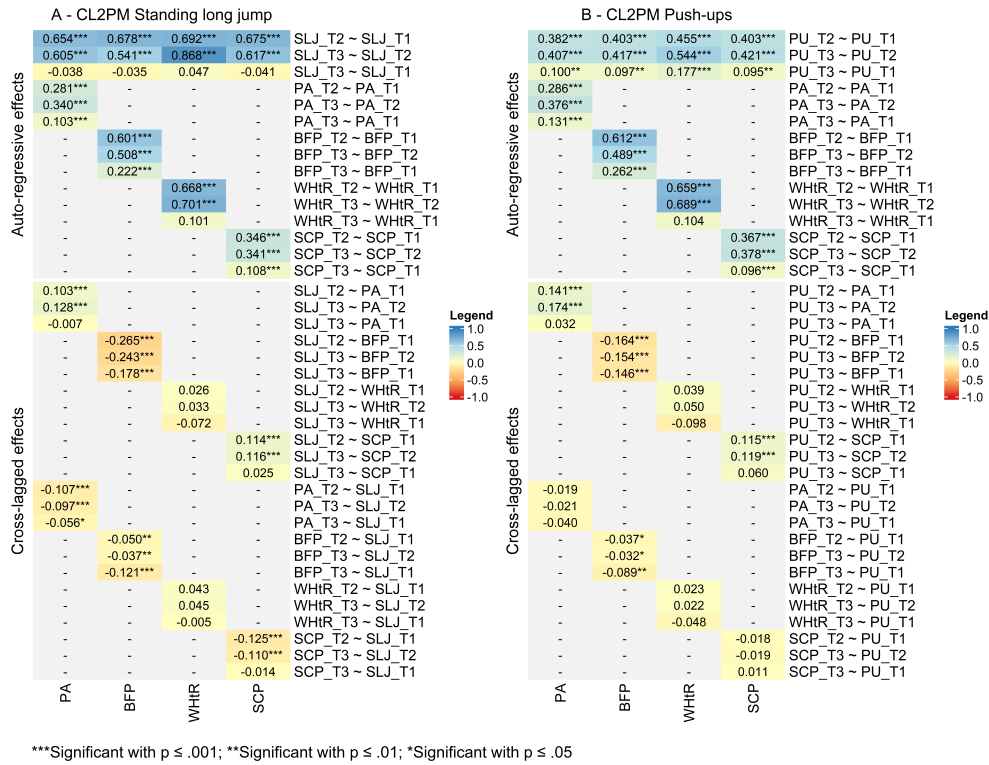


Fig. 3 Results of the Cross-Lagged Panel Models with lag-2. CL2PM Cross-Lagged Panel Model with lag-2; SLJ Standing long jump; PU Push-ups; T1 Baseline Measurement Wave; T2 Measurement Wave 1; T3 Measurement Wave 2; PA Physical activity; BFP Body fat percentage; WHtR Waist-to-height ratio; SCP Sports club participation

to T2 ($\beta = 0.103$ to 0.128 ; $p < .05$) and from T2 to T3 ($\beta = 0.141$ to 0.174 ; $p < .05$). Regarding body fat percentage, higher levels negatively affected performance levels across all paths ($\beta = -0.146$ to -0.265 ; $p < .05$). While the waist-to-height ratio did not significantly affect performance levels, sports club participation positively influenced performance levels from T1 to T2 ($\beta = 0.114$ to 0.115 ; $p < .05$) and from T2 to T3 ($\beta = 0.116$ to 0.119 ; $p < .05$). Higher performance levels in the Standing long jump negatively affected physical activity ($\beta = -0.056$ to -0.107 ; $p < .05$) and body fat percentage ($\beta = -0.037$ to -0.121 ; $p < .05$) across all paths, as well as sports club participation from T1 to T2 ($\beta = -0.125$; $p < .05$) and from T2 to T3 ($\beta = -0.110$; $p < .05$). Higher performance levels in Push-ups negatively affected body fat

percentage across all paths ($\beta = -0.032$ to -0.089 ; $p < .05$). An overview of all path models for the conducted CL2PMs are depicted in the supplement (see Additional file 1; Supplementary Figures 17-24).

4 Discussion

The present study examined the longitudinal associations between Muscular fitness, physical activity, body composition, and sports club participation from childhood to adulthood. By employing both traditional Cross-Lagged Panel Models (CLPMs) and extended Cross-Lagged Panel Models with lag-2 effects (CL2PMs), this study provides comprehensive insights into how these variables interact and influence each other throughout physical development. Overall, the findings indicate that Muscular fitness and its components demonstrate medium-to-large stability over time and that behavioral and body composition factors play a significant role in shaping the long-term development of Muscular fitness.

4.1 Cross-Lagged Panel results

Both the CLPM and CL2PM analyses revealed highly consistent patterns in the longitudinal interplay between Muscular fitness measures, physical activity, body composition, and sports club participation. Across both modeling approaches, Muscular fitness showed the largest autoregressive effects ($\beta = 0.944$ – 0.975), confirming previous evidence that Muscular fitness exhibit substantial tracking from childhood through adolescence [8, 17–20]. Following on from this point, it must be mentioned that the size of the autoregressive effects is partly due to the fact that Muscular Fitness is a factor score based on the three individual test items. Among these, the Standing long jump demonstrated the highest autoregressive coefficients, suggesting that explosive leg power represents a particularly stable dimension of muscular performance [19]. Similarly, physical activity, body fat percentage, waist-to-height ratio, and sports club

participation demonstrated medium-to-large stability across all measurement points supporting the notion that behavioral [53–56] and physiological patterns [57–60] established early in life persist over time. Within these predictors, body fat percentage and waist-to-height ratio showed the strongest autoregressive effects, underlining the relative stability of body composition indicators throughout youth [61].

The cross-lagged pathways in both models consistently indicated that higher levels of physical activity, sports club participation, as well as lower body fat percentage, predicted higher Muscular fitness at subsequent time points. These associations were small-to-large in magnitude, representing meaningful but modest longitudinal effects that align with prior findings linking higher physical activity [24, 25] and organized sports engagement to improved muscular strength and endurance [22, 23]. Among these predictors the body fat percentage exhibited the highest effects, indicating that it has more influence on shaping Muscular fitness and performance development than activity indicators. Further, the negative association between body fat percentage and later Muscular fitness supports evidence that excess body fat or obesity can reduce muscle strength or endurance [62, 63]. Conversely, Muscular fitness negatively predicted subsequent body fat percentage, suggesting that enhanced fitness fosters healthier body composition [2, 15].

Beyond these general patterns, the directional strength of the cross-lagged associations differed between variables and models. Muscular fitness more strongly predicted later body fat percentage and waist-to-height ratio than the reverse, whereas it was more strongly shaped by physical activity and sports club participation than it influenced them. At the test level, Standing long jump, Push-ups, and Sit-ups were more strongly influenced by physical activity, body fat percentage, and sports club participation than vice versa, while all three predicted waist-to-height ratio more strongly than they were predicted by it. The CL2PM largely confirmed this pattern. Standing

783 long jump was more strongly influenced by physical activity and body fat percent-
784 age than it influenced these variables, while Push-up performance, consistent with
785 the CLPM, was predominantly influenced by physical activity, body fat percentage,
786 and sports club participation. These parallels across models increase confidence in the
787 temporal ranking of effects, indicating that behavioral and anthropometric factors are
788 primary drivers of muscular performance development rather than outcomes shaped
789 by performance alone.

794 A closer inspection of the CL2PMs, which confirmed the same overall directional
795 patterns as the CLPMs, further revealed nuanced differences in autoregressive stabil-
796 ity across performance tests. For the Standing long jump, significant autoregressive
797 effects were found only from T1 to T2 and from T2 to T3, indicating temporal stability
798 across consecutive but not more distant measurement points. In contrast, for Push-up
799 performance, significant pathways were also observed from T1 to T3, although these
800 effects were below the threshold for small effects ($\beta \geq 0.2$), suggesting limited long-
801 term carryover. Regarding the predictors, higher physical activity levels positively
802 influenced both Standing long jump and Push-up performance at later time points,
803 with medium-to-large effects [24, 25]. Furthermore, sports club participation remained
804 a consistent predictor of higher performance [22, 23] from T1 to T2 and from T2
805 to T3, but not across the longer T1–T3 interval. In contrast, higher body fat per-
806 centage consistently predicted lower performance levels [62, 63], with large negative
807 effects, and higher performance levels consistently predicted higher body fat percent-
808 age [2, 15]. Thus, reinforcing the inverse link between body fat percentage and relative
809 strength performance. The waist-to-height ratio showed inconclusive cross-lagged asso-
810 ciations, suggesting that it represents a less dynamic or responsive indicator of body
811 composition compared with body fat percentage.

Interestingly, both modeling approaches revealed small negative associations between early muscular performance and later physical activity or sports club participation. These effects appeared only for selected performance measures and may indicate that individuals with initially higher performance levels subsequently reduce their engagement in structured activities. Such patterns could reflect behavioral compensation mechanisms, whereby high initial physical performance leads to a perceived reduction in the need for further training or organized activity. Another, in our view plausible explanation, is that individuals with higher fitness levels may have reported their physical activity more accurately with less over-reporting, which is commonly observed in self-reported activity measures [64, 65]. Although these effects were small and not consistently observed across all models or time intervals, their recurrence across both CLPM and CL2PM analyses suggests that they may represent subtle but genuine behavioral adjustments rather than random fluctuations. The overall convergence between CLPM and CL2PM results thus enhances confidence in the temporal stability and direction of these associations, indicating that the underlying mechanisms are robust to different model specifications.

4.2 Practical implications

Taken together, the findings highlight a dynamic yet stable interplay between Muscular fitness, activity behaviors, and body composition throughout developmental stages. The medium-to-large autoregressive effects underscore the high temporal stability of these constructs, while the small-to-medium cross-lagged effects point to incremental but meaningful changes across time. The particularly strong stability of body fat percentage and waist-to-height ratio, alongside the strong autoregressive effects of Muscular fitness, indicates that individuals with low Muscular fitness [8, 18–20] and unfavorable body composition [57–60] in childhood are highly likely to maintain these patterns later in life. This persistence is concerning from a public health perspective, as

it may reinforce long-term health inequalities. Early interventions are therefore essential to disrupt these trajectories and support children and adolescents with low fitness or high body fat levels in improving their physical health. From a broader health promotion perspective, these results underscore the need to create environments that promote regular muscle-strengthening activities from an early age [66]. This includes improving access to organized sports clubs, commercial sports providers, and freely accessible strength-training opportunities (e.g., calisthenics parks or outdoor fitness trails). By reducing structural barriers and increasing opportunities for participation, such measures may support children and adolescents in meeting the national recommendations for physical activity and exercise promotion in Germany [67] as well as the World Health Organization’s youth physical activity guidelines [16].

4.3 Strengths and Limitations

Key strengths of this study include its large, nationally representative drawn sample, the longitudinal design spanning crucial developmental periods, the robust measures of Muscular Fitness, and the application of advanced cross-lagged modeling techniques to test bidirectional pathways that also generate more internally valid findings. The combination of CLPMs and CL2PMs allowed for a comprehensive assessment of both direct and delayed associations, confirming that the relationships remain stable across analytical approaches. Nevertheless, several limitations should be considered. Physical activity was assessed via self-report, which may introduce recall and social desirability biases which can lead to over- or underreporting [68]. Additionally, physical activity was calculated by summation of activities in different settings, which can lead to distortions since the same activity values may be recorded multiple times. While Cross-Lagged Panel Models provide temporal insights, they of course cannot guarantee causality, and residual confounding by unmeasured factors (e.g., maturation, nutrition, motivation) remains possible. The Sit-up test and the composite Muscular fitness

score could not be included in the CL2PM analyses, as three consecutive measurement points are required for estimation. Another methodological limitation concerns the unequal and relatively long intervals between measurement waves—each spanning approximately three years—which may introduce interindividual variance in developmental timing and measurement non-invariance across waves. Additionally, though our sample was representatively drawn we were not able to apply sample weighting to correct for selection bias as well as non-response and to adjust for demographic differences.

4.4 Conclusions

This study demonstrates that Muscular fitness, physical activity, body fat percentage, and sports club participation are closely interrelated and mutually reinforcing from childhood into early adulthood. Small-to-large cross-lagged effects suggest that sustained engagement in physical activity and organized sports, alongside favorable body fat percentage, contributes to improved Muscular fitness and performance development over time. The varying strengths of the cross-lagged paths further indicate that the body fat percentage exerts a stronger influence on overall Muscular fitness and performance development than activity indicators. At the same time, the body composition indicators were influenced more strongly by Muscular fitness than they influenced it, while on performance level physical activity, body fat percentage, and sports club participation had a stronger influence than they were influenced. Overall, the cross-lagged effects on performance level were stronger than for overall Muscular fitness, underscoring their central role in shaping performance development. Furthermore, the strong autoregressive effects highlight the persistence of low Muscular fitness and high body fat percentage, underscoring the need for early, targeted interventions to reduce health disparities and support the development of lifelong fitness and health.

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973

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976

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989 **Conflict of interest/Competing interests**

990

991 The authors declare no conflict of interest/competing interests.
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995 **Ethics approval and consent to participate**

996

997 All procedures performed in studies involving human participants or on human tis-
998 sue were in accordance with the ethical standards of the institutional and/or national
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1003 Commissioner for Data Protection and Freedom of Information was informed about the
1004 study and approved it. In-formed consent was obtained from all individual participants
1005
1006
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1008
1009 included in the study.
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Consent for publication	1013
	1014
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Data availability	1018
	1019
The datasets generated and analysed during the current study are not publicly avail-	1020
able due to the strict ethical standards required by the German Federal Office for the	1021
Protection of Data, to which study investigators are obliged to comply, but are avail-	1022
able from the project management of the MoMo study at the Karlsruhe Institute of	1023
Technology upon reasonable request.	1024
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Materials availability	1030
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Code availability	1035
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Author contribution	1040
	1041
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and KS developed and conducted the statistical analysis. All authors were involved	1043
with the interpretation and review of the results. All authors were involved with	1044
drafting the manuscript. TK revised the manuscript according to feedback from all	1045
authors, who were involved in critical revisions and provided important intellectual	1046
content.	1047
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