Physical activity and obesity mediate the association between childhood motor function and adolescents’ academic achievement

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The global epidemic of obesity and physical inactivity may have detrimental implications for young people’s cognitive function and academic achievement. This prospective study investigated whether childhood motor function predicts later academic achievement via physical activity, fitness, and obesity. The study sample included 8,061 children from the Northern Finland Birth Cohort 1986, which contains data about parent-reported motor function at age 8 y and self-reported physical activity, predicted cardiorespiratory fitness (cycle ergometer test), obesity (body weight and height), and academic achievement (grades) at age 16 y. Structural equation models with unstandardized (B) and standardized (β) coefficients were used to test whether, and to what extent, physical activity, cardiorespiratory fitness, and obesity at age 16 mediated the association between childhood motor function and adolescents’ academic achievement.

Physical activity was associated with a higher grade-point average, and obesity was associated with a lower grade-point average in adolescence. Furthermore, compromised motor function in childhood had a negative indirect effect on adolescents’ academic achievement via physical inactivity (B = −0.023, 95% confidence interval = −0.031, −0.015) and obesity (B = −0.025, 95% confidence interval = −0.039, −0.011), but not via cardiorespiratory fitness. These results suggest that physical activity and obesity may mediate the association between childhood motor function and adolescents’ academic achievement. Compromised motor function in childhood may represent an important factor driving the effects of obesity and physical inactivity on academic underachievement.

Results

The sex-specific distributions of parent-reported motor function, self-reported physical activity, predicted cardiorespiratory fitness, obesity, academic achievement, and all contextual variables from the original data are presented in Table S1. At age 8 y, boys were more likely to have compromised motor function compared with girls (P < 0.001). At age 16 y, girls (M = 8.1, SD 0.8) had higher academic achievement levels, as indicated by grade-point average (GPA), compared with boys (M = 7.5, SD 0.9) (P < 0.001). The mean metabolic equivalent of task (MET) hours per week were 32.8 (SD 17.9) for boys and 28.7 (SD 15.5) for girls (P < 0.001). The mean peak oxygen consumption (VO2peak in mL·kg−1·min−1) was 49.1 (SD 9.7) among boys and 35.4 (SD 6.4) among girls (P < 0.001). Boys were more often overweight or obese compared with girls (P = 0.001). Correlations of the variables are presented in Table S2.

Author contributions: M.T.K., E.S., A.R., T.A., M.-R.J., and T.T. designed research; A.T., M.T.K., A.K., and M.K. analyzed data; and M.T.K., E.S., and A.R. wrote the paper.

The authors declare no conflict of interest.

The article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1214574110/-/DCSupplemental.
The structural equation models (with standardized $\beta$-coefficients) that describe the mediating effects of physical activity, fitness, and obesity on the association between childhood motor function at age 8 y and adolescents’ academic achievement at age 16 y are described in Fig. 1. The model fitted the data well in terms of root-mean-square error of approximation (0.045) and comparative-fit index (0.974). Unstandardized (B) and standardized ($\beta$) regression coefficients conditional on all of the variables in the structural equation modeling (SEM) analysis are shown in Table 1. Table 2 presents the indirect and total effects (unstandardized B coefficients) of childhood motor function and adolescents’ physical activity, fitness, and obesity levels on academic achievement, calculated assuming that the relations depicted in Fig. 1 are correct. Initially, childhood motor function had a direct effect on adolescents’ academic achievement, but it did not remain statistically significant after taking into account the mediating effects of physical inactivity and obesity.

The unstandardized B coefficients suggested that compromised motor function in childhood predicted lower levels of physical activity (B = −4.673), poor cardiorespiratory fitness (B = −1.460), and higher levels of obesity (B = 0.287) in adolescence (Table 1). Furthermore, higher levels of physical activity were associated with a higher GPA (B = 0.005) and obesity with a lower GPA (B = −0.086) in adolescence. Compromised motor function had a negative indirect effect on academic achievement via lower levels of physical activity (B = −0.023) and obesity (B = −0.025), but not via cardiorespiratory fitness (Table 2). The estimated total effect of compromised motor function on academic achievement (B = −0.042) corresponded to a decrease of 0.04 units in the GPA. The described model explained 31% of the variance in the GPA, as indicated by the $R^2$ value (0.31).

We also fitted structural equation models separately for boys ($n = 4,126$) and girls ($n = 3,935$), and compared the estimates with those obtained from an analysis including both sexes. In general, there were no significant differences in the estimates between boys and girls, except in the association between compromised motor function and cardiorespiratory fitness, which was attenuated among girls [B = −0.135, 95% confidence interval (CI) = −0.619, 0.349] compared with boys (B = −2.574, 95% CI = −4.275, −0.873). We further compared the distributions of all of the variables used in the present study between the sample with complete cases only (information available on all of the variables in the model) ($n = 2,865$) and the full study sample, including those participants who had missing values in at least one variable ($n = 8,061$). Participants in the full sample were more likely to have problems in learning to read (12% vs. 10%), write (17% vs. 14%), and do mathematics (9% vs. 6%), to have a mother with basic-level education (11% vs. 9%), to have a lower GPA (7.8 vs. 8.0), and to be less physically active (mean MET hours per week = 30.7 vs. 32.3) compared with participants with complete data. We then fitted the models for complete cases only, and compared the estimates with those obtained from an analysis including all cases. In general, all of the estimates pointed in the same direction and were approximately of the same magnitude as in the all-cases analyses. However, the association between compromised motor function and cardiorespiratory fitness was attenuated in the complete-case analyses (B = −0.442, 95% CI = −1.034, 0.151) compared with the all-cases analyses (B = −1.460, 95% CI = −2.426, −0.494). The variables with missing values were included in the model used for the all-cases analyses; therefore, imbalances between participation and nonparticipation at any given time were implicitly taken into account in the all-cases analyses.

**Discussion**

Our data provide evidence that physical activity and obesity mediate the association between childhood motor function and adolescents’ academic achievement. Compromised motor function in childhood may serve as a significant underlying factor for the effects of obesity and physical inactivity on academic underachievement, which has recently attracted attention as a growing global education and public health concern (4). Poor motor activity in the early school years can contribute to setting the child on a negative developmental trajectory.

There is a growing body of literature demonstrating that lifestyle factors such as excess sedentary behavior and an unhealthy diet may...
Our results partly support previous activity on academic performance (4, 5) and suggest that involvement in physical activity is associated with improved self-concept and increased academic performance (24). Physical activity may induce arousal and reduce boredom, leading to an increase in attention span and mnemonic processes, which may partly explain the positive association between physical activity and academic achievement.

The present study contributes to the knowledge pool by demonstrating causal candidate pathways from childhood motor function to adolescents’ academic achievement via obesity and physical activity. Our results are in line with previous studies in which compromised motor function in childhood predicted adolescent obesity (16, 29, 30), physical inactivity (17, 31), and poor cardiorespiratory fitness (14, 16). It has been suggested that there is a negative spiral of disengagement in physical activity with low motor competence, low perceptions of motor skill competence, physical inactivity, and poor fitness, leading to obesity, which, in turn, negatively influences the other factors (14). However, cardiorespiratory fitness did not mediate the association between childhood motor function and adolescents’ academic achievement in the present study when the mediating effects of physical activity and obesity were taken into account. Evidence on this is mixed and inconclusive, with some studies indicating a positive association and others showing no association (4). Our results add to the current knowledge by indicating complex interrelations and shared, as well as independent, effects of physical activity and obesity on academic achievement. This emphasizes the need to better understand the mediators for the effects of physical activity and obesity on academic achievement. It is also possible that the

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Table 1. Relations between childhood motor function and adolescents’ physical activity, cardiorespiratory fitness, obesity level, and academic achievement (n = 8,061)

<table>
<thead>
<tr>
<th>Model</th>
<th>B</th>
<th>SE</th>
<th>95% CI</th>
<th>P value</th>
<th>β</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade-point average*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Physical activity</td>
<td>0.005</td>
<td>0.001</td>
<td>0.003, 0.007</td>
<td>&lt;0.001</td>
<td>0.091</td>
</tr>
<tr>
<td>Cardiorespiratory fitness</td>
<td>−0.003</td>
<td>0.002</td>
<td>−0.007, 0.001</td>
<td>0.225</td>
<td>−0.032</td>
</tr>
<tr>
<td>Obesity level</td>
<td>−0.086</td>
<td>0.021</td>
<td>−0.127, −0.045</td>
<td>&lt;0.001</td>
<td>−0.094</td>
</tr>
<tr>
<td>Early academic impairment</td>
<td>−0.341</td>
<td>0.015</td>
<td>−0.370, −0.312</td>
<td>&lt;0.001</td>
<td>−0.365</td>
</tr>
<tr>
<td>Mother’s higher education</td>
<td>0.721</td>
<td>0.048</td>
<td>0.627, 0.815</td>
<td>&lt;0.001</td>
<td>0.266</td>
</tr>
<tr>
<td>Mother’s upper secondary education</td>
<td>0.226</td>
<td>0.039</td>
<td>0.150, 0.302</td>
<td>&lt;0.001</td>
<td>0.106</td>
</tr>
<tr>
<td>Sex (female vs. male)</td>
<td>0.565</td>
<td>0.038</td>
<td>0.491, 0.639</td>
<td>&lt;0.001</td>
<td>0.308</td>
</tr>
<tr>
<td>Physical activityb</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compromised motor function</td>
<td>−4.673</td>
<td>0.644</td>
<td>−5.935, −3.411</td>
<td>&lt;0.001</td>
<td>−0.207</td>
</tr>
<tr>
<td>Cardiorespiratory fitness</td>
<td>25.513</td>
<td>2.253</td>
<td>21.097, 29.929</td>
<td>&lt;0.001</td>
<td>0.195</td>
</tr>
<tr>
<td>Obesity level</td>
<td>−0.252</td>
<td>0.324</td>
<td>−0.887, 0.383</td>
<td>0.437</td>
<td>−0.016</td>
</tr>
<tr>
<td>Mother’s higher education</td>
<td>5.055</td>
<td>0.802</td>
<td>3.483, 6.627</td>
<td>&lt;0.001</td>
<td>0.102</td>
</tr>
<tr>
<td>Mother’s upper secondary education</td>
<td>2.034</td>
<td>0.644</td>
<td>0.772, 3.296</td>
<td>0.002</td>
<td>0.052</td>
</tr>
<tr>
<td>Sex (female vs. male)</td>
<td>−4.248</td>
<td>0.450</td>
<td>−5.130, −3.366</td>
<td>&lt;0.001</td>
<td>−0.126</td>
</tr>
<tr>
<td>Cardiorespiratory fitness</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compromised motor function</td>
<td>−1.460</td>
<td>0.493</td>
<td>−2.426, −0.494</td>
<td>0.003</td>
<td>−0.102</td>
</tr>
<tr>
<td>Physical activity</td>
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<td>2.253</td>
<td>21.097, 29.929</td>
<td>&lt;0.001</td>
<td>0.195</td>
</tr>
<tr>
<td>Obesity level</td>
<td>−0.458</td>
<td>0.349</td>
<td>−0.817, −0.103</td>
<td>&lt;0.001</td>
<td>−0.571</td>
</tr>
<tr>
<td>Mother’s higher education</td>
<td>1.770</td>
<td>0.565</td>
<td>0.663, 2.877</td>
<td>0.002</td>
<td>0.056</td>
</tr>
<tr>
<td>Mother’s upper secondary education</td>
<td>1.132</td>
<td>0.419</td>
<td>0.311, 1.953</td>
<td>0.007</td>
<td>0.046</td>
</tr>
<tr>
<td>Sex (female vs. male)</td>
<td>−13.817</td>
<td>0.250</td>
<td>−14.307, −13.327</td>
<td>&lt;0.001</td>
<td>−0.649</td>
</tr>
<tr>
<td>Obesity level</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compromised motor function</td>
<td>0.287</td>
<td>0.048</td>
<td>0.193, 0.381</td>
<td>&lt;0.001</td>
<td>0.213</td>
</tr>
<tr>
<td>Physical activity</td>
<td>−0.252</td>
<td>0.324</td>
<td>−0.887, 0.383</td>
<td>0.437</td>
<td>−0.016</td>
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<td>Cardiorespiratory fitness</td>
<td>−4.587</td>
<td>0.349</td>
<td>−5.271, −3.903</td>
<td>&lt;0.001</td>
<td>−0.571</td>
</tr>
<tr>
<td>Mother’s higher education</td>
<td>−0.266</td>
<td>0.075</td>
<td>−0.413, −0.119</td>
<td>&lt;0.001</td>
<td>−0.090</td>
</tr>
<tr>
<td>Mother’s upper secondary education</td>
<td>−0.165</td>
<td>0.056</td>
<td>−0.275, −0.055</td>
<td>0.003</td>
<td>−0.071</td>
</tr>
<tr>
<td>Sex (female vs. male)</td>
<td>−0.138</td>
<td>0.035</td>
<td>−0.207, −0.069</td>
<td>&lt;0.001</td>
<td>−0.068</td>
</tr>
<tr>
<td>Compromised motor function</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Early academic impairment</td>
<td>0.309</td>
<td>0.032</td>
<td>0.246, 0.372</td>
<td>&lt;0.001</td>
<td>0.420</td>
</tr>
</tbody>
</table>

*The grade-point average (scale 4–10) included mother tongue (in most cases Finnish or Swedish), first foreign language (started at grade 3), second foreign language (started at grade 7), mathematics, biology, geography, physics, chemistry, religion or ethics, history, music, visual arts, physical education, crafts, and home economics.

Physical-activity level was defined as metabolic equivalent hours per week based on the intensity and volume of physical activity engaged in outside school hours, including commuting to and from school.

Cardiorespiratory fitness was measured with a submaximal cycle ergometer test and expressed as peak oxygen uptake in mL·kg⁻¹·min⁻¹.

Obesity level was defined using the IDF age-specific cutoff points for BMI. The BMI was calculated as the weight divided by the square of the height (kg/m²).
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Table 2. Indirect and total effects of childhood motor function and adolescents’ physical activity, fitness, and obesity level on academic achievement (n = 8,061)

<table>
<thead>
<tr>
<th>Model</th>
<th>B</th>
<th>SE</th>
<th>95% CI</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade-point average*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total effect</td>
<td>−0.042</td>
<td>0.008</td>
<td>−0.058, −0.026</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Total indirect effect</td>
<td>−0.042</td>
<td>0.008</td>
<td>−0.058, −0.026</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>MF–PA8–GPA4*</td>
<td>−0.023</td>
<td>0.004</td>
<td>−0.031, −0.015</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>MF–CRF–GPA4*</td>
<td>0.004</td>
<td>0.004</td>
<td>−0.004, 0.012</td>
<td>0.314</td>
</tr>
<tr>
<td>MF–OL4–GPA4*</td>
<td>−0.025</td>
<td>0.007</td>
<td>−0.039, −0.011</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

CRF, cardiorespiratory fitness; MF, motor function; OL, obesity level; PA, physical activity.

The measures of motor function were based on parental reports rather than on more-accurate objective measurements and are, thus, susceptible to inaccuracy (37). It is possible that poor parental understanding of motor development contributes to the measures of parent-reported motor function. Furthermore, the criterion validity of the questions used to measure parent-reported motor function has not been established in Finnish children. However, the prevalence of compromised motor function in our study was comparable to the prevalence reported in previous studies. In addition, we have produced evidence supporting the convergent validity of these questions, including the previously reported associations of these measures of parent-reported motor function with physically active play in childhood and with physical activity and cardiorespiratory fitness in adolescence (17). Our study relied on adolescents’ self-reported physical activity, which might contain relatively large measurement errors and social desirability bias (38, 39). Physical activity, fitness, obesity, and academic achievement were measured at 16 y, limiting the interpretation of causality in explaining academic achievement. It would have been useful and informative to have all these factors measured at several time points to enable the examination of how these variables change with respect to each other over time. However, one of the indications of successful selection and model fitting was, for example, the fact that the assumed models explained a high percentage (~31%) of the total variation in academic achievement, yet it is likely that a notable proportion of this variation was explained by sex and maternal education.

In summary, using a large European population-based cohort, we found evidence that physical activity and obesity mediate the association between childhood motor function and adolescents’ academic achievement. Compromised motor function in childhood may represent an important factor driving the effects of obesity and physical inactivity on academic underachievement.

Materials and Methods

For a full description of all materials and methods, see SI Materials and Methods.

Participants. The study sample consisted of a prospective mother–child birth cohort, the Northern Finland Birth Cohort 1986, which at baseline was composed of 5,432 infants whose expected date of birth was between July 1, 1985, and June 30, 1986, in the two northernmost provinces of Finland, Oulu and Lapland (40). Data collection commenced during the mothers’ pregnancy, and follow-up surveys were carried out when the children were 7–8 y old (1992–1994) (hereafter “8 y”), and 15–16 y old (2001–2002) (hereafter “16 y”). The present analysis included those 8,061 children (4,126 boys and 3,935 girls) who had complete information on academic achievement at age 16. Informed consent was obtained from all participants and their parents, and the research protocol was approved by the Ethics Committee of Northern Ostrobotnia Hospital District.

Parent-Reported Motor Function. Gross motor skills at the age of 8 y were measured through the parents’ questionnaire. The parents were asked the following questions: “Can your child tie his or her shoelaces?” [response alternatives: (i) yes, (ii) no, and (iii) cannot say]; “Can your child usually catch a ball in a game?” [response alternatives: (i) mostly, (ii) sometimes, and (iii) hardly ever]; and “Can your child skate?” [response alternatives: (i) yes, (ii) no, and (iii) cannot say]. Fine motor skills were assessed with the following questions: “Is your child’s pencil use awkward?” [response alternatives: (i) yes, (ii) no, and (iii) cannot say]; “Can your child hold a pen or pencil?” [response alternatives: (i) yes, (ii) no, and (iii) cannot say]; “Can your child hold a toy or put clothes on?” [response alternatives: (i) yes, (ii) no, and (iii) cannot say]. The measures of motor function were based on parental reports rather than on more-accurate objective measurements and are, thus, susceptible to inaccuracy (37). It is possible that poor parental understanding of motor development contributes to the measures of parent-reported motor function. Furthermore, the criterion validity of the questions used to measure parent-reported motor function has not been established in Finnish children. However, the prevalence of compromised motor function in our study was comparable to the prevalence reported in previous studies. In addition, we have produced evidence supporting the convergent validity of these questions, including the previously reported associations of these measures of parent-reported motor function with physically active play in childhood and with physical activity and cardiorespiratory fitness in adolescence (17). Our study relied on adolescents’ self-reported physical activity, which might contain relatively large measurement errors and social desirability bias (38, 39). Physical activity, fitness, obesity, and academic achievement were measured at 16 y, limiting the interpretation of causality in explaining academic achievement. It would have been useful and informative to have all these factors measured at several time points to enable the examination of how these variables change with respect to each other over time. However, one of the indications of successful selection and model fitting was, for example, the fact that the assumed models explained a high percentage (~31%) of the total variation in academic achievement, yet it is likely that a notable proportion of this variation was explained by sex and maternal education.

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For a full description of all materials and methods, see SI Materials and Methods.

Participants. The study sample consisted of a prospective mother–child birth cohort, the Northern Finland Birth Cohort 1986, which at baseline was composed of 5,432 infants whose expected date of birth was between July 1, 1985, and June 30, 1986, in the two northernmost provinces of Finland, Oulu and Lapland (40). Data collection commenced during the mothers’ pregnancy, and follow-up surveys were carried out when the children were 7–8 y old (1992–1994) (hereafter “8 y”) and 15–16 y old (2001–2002) (hereafter “16 y”). The present analysis included those 8,061 children (4,126 boys and 3,935 girls) who had complete information on academic achievement at age 16. Informed consent was obtained from all participants and their parents, and the research protocol was approved by the Ethics Committee of Northern Ostrobotnia Hospital District.

Parent-Reported Motor Function. Gross motor skills at the age of 8 y were measured through the parents’ questionnaire. The parents were asked the following questions: “Does your child enjoy doing something or fall down often?” [response alternatives: (i) yes, (ii) no, and (iii) cannot say]; “Can your child usually catch a ball in a game?” [response alternatives: (i) mostly, (ii) sometimes, and (iii) hardly ever]; and “Can your child skate?” [response alternatives: (i) yes, (ii) no, and (iii) cannot say]. Fine motor skills were assessed with the following questions: “Is your child’s pencil use awkward?” [response alternatives: (i) yes, (ii) no, and (iii) cannot say]; “Can your child hold a pen or pencil?” [response alternatives: (i) yes, (ii) no, and (iii) cannot say]; “Can your child hold a toy or put clothes on?” [response alternatives: (i) yes, (ii) no, and (iii) cannot say]. The measures of motor function were based on parental reports rather than on more-accurate objective measurements and are, thus, susceptible to inaccuracy (37). It is possible that poor parental understanding of motor development contributes to the measures of parent-reported motor function. Furthermore, the criterion validity of the questions used to measure parent-reported motor function has not been established in Finnish children. However, the prevalence of compromised motor function in our study was comparable to the prevalence reported in previous studies. In addition, we have produced evidence supporting the convergent validity of these questions, including the previously reported associations of these measures of parent-reported motor function with physically active play in childhood and with physical activity and cardiorespiratory fitness in adolescence (17). Our study relied on adolescents’ self-reported physical activity, which might contain relatively large measurement errors and social desirability bias (38, 39). Physical activity, fitness, obesity, and academic achievement were measured at 16 y, limiting the interpretation of causality in explaining academic achievement. It would have been useful and informative to have all these factors measured at several time points to enable the examination of how these variables change with respect to each other over time. However, one of the indications of successful selection and model fitting was, for example, the fact that the assumed models explained a high percentage (~31%) of the total variation in academic achievement, yet it is likely that a notable proportion of this variation was explained by sex and maternal education.

In summary, using a large European population-based cohort, we found evidence that physical activity and obesity mediate the association between childhood motor function and adolescents’ academic achievement. Compromised motor function in childhood may represent an important factor driving the effects of obesity and physical inactivity on academic underachievement.
Self-Reported Physical Activity, Predicted Cardiorespiratory Fitness, and Obesity. Self-reported physical activity outside school hours was evaluated separately for moderate-to-vigorous physical activity and light physical activity at age 16 y by asking participants, “How many hours a week all together do you participate in (a) brisk and (b) light physical activity outside school hours?” In the questionnaire, the term “brisk” was defined as physical activity causing at least some sweating and shortness of breath (here referred to as moderate-to-vigorous-intensity physical activity), whereas the term “light physical activity” was defined as causing no sweating or shortness of breath. In addition, the adolescents were asked about their daily time spent in physically active commutes to and from school. The response alternatives (not at all, less than 20 min, 20–39 min, 40–59 min, and at least 1 h per day) were multiplied by 5 (5 school days a week) to correspond to 0, 1, 2.5, 3.75, and 5 h/week (41). The physical-activity level was converted into MET hours per week based on the intensity and the volume of physical activity engaged in outside school hours, including commuting to and from school (in this study, referred to as “physical activity”). A MET-intensity value of three METs was used for light physical activity, five METs for brisk physical activity, and four METs for commuting physical activity in the calculations (42). The test–retest reliability of these physical-activity questions among Finnish adolescents aged 15–16 y has been reported to be good (41). The intraclass correlation coefficient for physical-activity levels described in terms of quintiles of MET hours per week was 0.70 (95% CI = 0.58–0.80), and the proportion of subjects who were classified in exactly the same category or next to the same category in two different tests was 86%.

Predicted cardiorespiratory fitness (in this study, referred to as “cardiorespiratory fitness”) was measured during a health examination at age 16 (n = 5,375) with a submaximal cycle ergometer test and expressed as peak oxygen uptake in mL·kg·min⁻¹. The exercise test protocol included two incremental work stages of 4 min each on a bicycle ergometer (model 818E, Monark). Peak oxygen uptake was calculated based on the heart-rate response during submaximal work stages. The method has been validated against directly measured VO₂peak during the maximal exercise test and has been previously described in detail (43). The cycle ergometer test is likely to be a relatively objective measure of physical fitness for young people, regardless of their motor development (17).

At the age of 16 y, the adolescents self-reported their body weight and height in the postal questionnaire, and these were measured in the health examination. Self-reported body weight and height were used for those who failed to attend the health examination. Body mass index (BMI) was calculated as the individual’s weight divided by the square of the height (kg/m²). Obesity was defined using the International Obesity Task Force (IOTF) age-specific cutoff points for BMI (44).

Learning and Education. Information on academic achievement was provided by the National Application Register for Upper Secondary Education, Finland, based on nationally comparable grades of the final assessment of basic education. The grades refer to numerical assessment on a scale of 4–10, where 4 denotes failure (US grade F) and 10 denotes excellent knowledge and skills (US grade A). They describe the level of performance in relation to the objectives of basic education at the end of grade 9 (age 16). The GPA was calculated as a measure of academic achievement based on the grades in the following school subjects: mother tongue (in most cases Finnish or Swedish), first foreign language (started at grade 3), second foreign language (started at grade 7), mathematics, biology, geography, physics, chemistry, religion or ethics, history, music, visual arts, physical education, crafts, and home economics. A Finnish GPA of 5.0–5.9 equals 1.0 (D) in US GPA, 6.0–6.9 equals 2.0 (C), 7.0–8.9 equals 3.0 (B), and 9.0–10.0 equals 4.0 (A).

Teachers assessed the children’s academic impairment at the age of 8 y by answering the question, “Does the child have difficulties with learning (i) to read, (ii) to write, or (iii) to do mathematics?” [response alternatives: (a) yes and (b) no] (45). Previous studies have reported that single-item teacher ratings are accurate measures of impairment, concurring with results of achievement tests (46, 47). These three components of impairment in learning were combined into one single latent variable, “early academic impairment.” The mother’s highest level of education when the adolescent was 16 y old was ascertained from the parents. The variable was categorized according to education-level categories used by the International Standard Classification of Education (48): (i) basic education, lasting 9 y or less, (ii) upper secondary education, lasting 10–12 y, and (iii) tertiary/higher education, lasting >13 y.

Statistical Analyses. We used structural equation modeling to explore and model the hypothesized underlying relations between the variables of interest. Four simultaneous equations were fitted, with academic achievement, physical activity, cardiorespiratory fitness, and obesity level at age 16 y as the outcome variables. Estimation of the parameters was carried out by the method of a robust weighted least-squares estimator. The multiple imputation by chained equations method (49) was used to generate multiple datasets of imputed data, which were analyzed using a special feature of Mplus (50). For comparison, we also estimated the model’s parameters separately for boys and girls and for complete cases only. Effect sizes of the predictors on the outcome variables were expressed as unstandardized (B) and standardized (β) estimates. The total effects of the predictors on the outcomes were computed by adding the indirect and direct effects together. The model was evaluated using the following goodness-of-fit indices: the comparative-fit index and the root-mean-square error of approximation. Modification indices (51) were used to detect misspecifications in the model. All of the analyses were conducted with SPSS software, version 19 (52), R version 2.12.2 (53), and Mplus, version 6.11 (50). All P values reported are two-sided.

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