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Device-based 24-h Physical Behavior by Thigh worn Accelerometry in a Nationwide Sample of Children and Adolescents from Germany: findings from the MoMo 2.0-Study

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Abstract

Background

The 24-hour physical behavior paradigm is a core construct for the development and health of children and adolescents. This study presents sex- and age-specific data on 24-hour time use, step count, and adherence to World Health Organization (WHO) physical activity (PA) guidelines in a nationwide sample of children and adolescents living in Germany.

Methods

Cross-sectional physical behavior data were collected from 2,642 children and adolescents using the thigh-worn activPAL4 device for seven consecutive days. Behaviors were categorized by intensity and summarized to calculate the overall PA level and adherence to the WHO PA guidelines from 2010 and 2020. Sex and age group differences were determined based on confidence intervals.

Results

The dataset included 1,584 participants (47.9% male, 52.1% female) with valid accelerometer data. Participants averaged 530±58 minutes of sleep, 602±85 minutes of sedentary behavior, 226±52 minutes of light PA, and 77±25 minutes of moderate-to-vigorous PA, alongside 12,907±3,918 steps daily. WHO 2010, and WHO 2020 PA

guideline fulfillment was 20.4%, and 74.5% respectively. Older participants spent less time sleeping and engaging in PA but more time in sedentary behavior. Boys had higher moderate-to-vigorous PA and overall sedentary behavior but less sitting time, while girls exhibited higher light PA and sleep in some age groups.

Conclusion

This study reports on 24-hour movement behaviors in a large, population-based sample of children and adolescents. The findings highlight distinct sex- and age-specific patterns in movement intensity and behaviors, emphasizing the importance of tailored strategies to promote PA and sleep, and to reduce sedentary behavior.

Keywords (3-8): physical activity, sedentary behavior, sleep, children, sensor

Introduction

Physical behavior (PB) is a key factor in the development and health of children and adolescents ¹. PB is defined by the combination of different behaviors that, in sum, relate to the full 24-hours of a day. It encompasses physical activity (PA), sedentary behavior (SB), and sleep ². Further differentiation can be made in intensity categories like light, moderate, and vigorous PA or in different behaviors like sitting, walking, and cycling with specific durations ³. Together these factors play an important role in different guidelines for isolated behaviors like the World Health Organization (WHO) guideline for moderate-to-vigorous PA (MVPA) ⁴ or the guideline for the 24-hour cycle of PB ⁵.

Historically, these behaviors have been assessed by self-report using questionnaires. This has changed over the past decades and device-based measurements are frequently employed and allow for high resolution data and avoiding recall bias ⁶. However, device-based estimates can differ by device, wear-protocol, data processing algorithm, and outcome parameter warranting established standardized reporting to improve comparativeness of the data ⁷. Additionally, the need for valid and transparent data processing to improve the body of evidence is high ⁸. Here, thigh-worn accelerometry has demonstrated superior accuracy in distinguishing sedentary and non-SBs, as well as identifying basic PA types, particularly when paired with data-driven activity classification algorithms ⁹. Notably, thigh-worn devices excel in detecting SBs (e.g., sitting and lying), standing postures, and specific activities such as cycling, outperforming accelerometers placed on the wrist or hip ¹⁰. While several nationwide studies utilize thigh-worn accelerometers in adults ^{3,11}, only few cohort studies published the prevalence of PB based on thigh worn accelerometry in children and adolescents and none including a broader age-span ^{12,13} despite their accuracy for PB monitoring ¹⁰ and their relevance for health ¹.

Consequently, the primary aim of this study is to present descriptive data on PBs, intensity categories, PA levels (PAL), and adherence to WHO PA guidelines ^{4,14} in a nationwide sample of children and adolescents living in Germany. Additionally, this study seeks to investigate sex- and age-specific patterns of PB and to provide a transparent reporting of the methodological approaches employed for data collection and processing.

Methods

Study Design

The Motorik-Module (MoMo) 2.0-Study assesses PB, physical fitness, and health in a nationwide representative cross-sectional cohort of children and adolescents aged 4-17 years living in Germany ¹⁵. Data collection took

place between September 2023 and December 2024. This study is a predecessor of the MoMo Study encompassing four measurement waves between 2003 and 2022 following a cohort-sequence design ¹⁶. Details on the sampling strategy, testing protocol, collected constructs etc. of the MoMo 2.0-Study can be found elsewhere ¹⁵. Briefly, the cohort sampling strategy involves two-stage randomization: random selection of 185 municipalities proportional to the population aged 4–17 years and inviting 140 (10 per age level) randomly chosen individuals per municipality. Participants register online and schedule appointments, with reminders sent to non-responders. The MoMo 2.0-Study included 86 different testing routes for data collection, and each route contained a maximum of three destinations and two testing days. Informed consent was provided by legal guardians or participants (for those over 15 years). The assessment at the study centers comprised a PA questionnaire, anthropometric measurements, motor performance tests, a health interview and the option to wear an accelerometer.

Accelerometry Sample

Participants who were tested in person during the MoMo 2.0-Study (N = 3,995) were invited to take part in the accelerometer sub-study. Exclusion criteria were allergies against medical patches, tape or polyethylene of low density, skin issues, a scheduled Magnetic Resonance Imaging or security check/metal detector (e.g. at the airport), and a missing informed consent. A total of 2,642 children and adolescents agreed to wear an accelerometer, 2,542 (96%) of these returned the accelerometer. Of those that returned the accelerometer and reported any problems during testing days, the most prevalent issues were that the device has fallen off, skin irritations, device failure and other reasons like illness or returning the device because of personal events.

Assessment Period and Protocol

The activPAL 4 (PALTechnologies Ltd., Scotland) was used for this study. The details used in this study are displayed in Appendix A. The sensor was placed on the front of the right thigh, 10 cm above the kneecap, while the knee was bent at 90°. Trained staff of the same sex as the participants placed the accelerometer on the participant's thigh to ensure consistent and accurate positioning. Participants were instructed using a standardized form. The accelerometer and data assessment were explained in detail and the participants were instructed to wear the sensor for eight consecutive days and only remove it in case of a Magnetic Resonance Imaging, security check, or skin irritation. If the device was removed for any reason, the participants should send it back to the study lead in the prepaid, pre-addressed padded envelope provided.

Data Processing

Data were downloaded using PALconnect (v9.1.0.148) and PALbatch (v9.1.0.77) was used to export the raw data as compressed and uncalibrated .csv-file. We used ActiPASS (Beta v2025.06.2) ¹⁷ to process the recorded raw 24-hour physical behavior data. ActiPASS is an open-source processing software for thigh-worn accelerometers that comprises non-wear time detection, activity type classification ^{9,18} as well as sleep detection ¹⁹ and step detection ²⁰. We used the default adult activity type classification thresholds, which have shown high accuracy in both laboratory and free-living conditions ⁹. For the walking intensities, we customized the default cadence thresholds for different intensities within ActiPASS using the age-specific heuristic thresholds recommended by Tudor-Locke et al. ²¹. Quality of the accelerometer data was visually checked for all cases flagged by the ActiPASS criteria. Problematic cases that showed implausible data due to e.g. reference position

errors were removed in this step. If the problem only occurred on certain days, data starting from this day was removed from the analysis.

The daily estimates were then processed to calculate weekly averages per day using R ²². To be included in the data, each participant had to have at least two weekdays and one weekend day with at least 20 hours of recording to represent a valid week ²³. Default PB categories by ActiPASS were used to define time spent in various intensities (table 1). The PAL value was calculated by multiplying the metabolic equivalent (MET) values with the time spent in the respective category and dividing the result by the total wear-time.

Table 1. ActiPASS physical behaviors, their respective metabolic equivalent and physical behavior category, metabolic equivalent

Physical behavior	Metabolic equivalent	Physical behavior intensity
Sleeping	0.9	Sleep
Lying	1.0	Sedentary behavior
Sitting	1.3	
Standing	1.55	Light physical activity
Moving	2.0	
Slow walking	2.0	
Other*	2.0	
Fast walking	4.0	Moderate-to-vigorous physical activity
Cycling	7.0	
Stair walking	8.0	
Running	10.0	

**"Other" activities without periodicity are classified as light physical activity with a fixed MET value of 2, while "Other" activities with periodicity are classified similarly to walking.*

WHO guideline

PA guideline adherence was assessed based on the 2010 WHO guideline ¹⁴ to enable comparison with previous MoMo waves and older results. According to these guidelines, adherence was defined as achieving at least 60 minutes of MVPA on each valid day. Adherence to the MVPA part of the 2020 WHO guidelines ⁴ was calculated. In this case, adherence was operationalized as achieving an average of at least 60 minutes of MVPA per valid day.

Sociodemographic variables

Participants' age and sex were assessed via questionnaire. Age was calculated based on the date of birth and date of data collection.

Body mass index (BMI) was calculated from measured height and weight without shoes and light clothing using a stadiometer (Seca 213) and a digital scale (Seca 813). BMI was first transformed into percentiles and then categorized into the categories severely underweight (<3rd percentile), underweight (3rd to 10th percentile), normal weight (10th to 90th percentile), overweight (90th to 97th percentile), obese (>97th percentile) ¹⁵.

Socioeconomic status was evaluated during the health interview conducted with a legal guardian and their child. A socioeconomic status index was derived by combining three components: parental education level, parental occupational status, and equivalized disposable household income. The socioeconomic status scores were subsequently divided into quintiles based on the MoMo 2.0 sample. Participants in the lowest quintile (3–11.7 points) were classified as having low socioeconomic status, while those in the highest quintile (18.4–21 points) were categorized as having high socioeconomic status. Participants falling within the middle three quintiles (11.8–18.3 points) were assigned to the medium socioeconomic status category ¹⁵.

Analyses

All data processing and data visualization was done with R and RStudio ²². The 95% confidence intervals were calculated based on the t-distribution for continuous outcomes and the normal approximation method for binary proportions. As the main focus on the article is to provide descriptive values, significant differences are judged by visually comparing the 95% confidence intervals. If the CIs overlap by half the length of one CI arm or less (corresponding to $p < .05$), the two means are interpreted as significantly different ²⁴.

Results

Following rigorous data quality checks and the application of valid week criteria, 1,584 participants (758 males, 47.9%, 825 females, 52.1%) out of the initial 2,642 (60%) were included in the final analysis. Sociodemographic data and the comparison to the whole MoMo 2.0 sample that reported at least sex and age can be found in Appendix B. Descriptively, sex, and age distributions are comparable between the samples, with small potential differences in body mass index and socioeconomic status.

Detailed sex- and age group specific descriptive results for all PB, intensities, and the PAL can be found in table 2. The CIs that are the base for the interpretation of the results and can be found in Appendix C.

152 Table 2. Sex and age-specific descriptive results of the physical behaviors, intensities, and the physical activity level. Reported are the mean values with the standard deviations in
153 brackets if applicable.

	Boys				Girls				Overall
	4-5 years (N=77)	6-10 years (N=342)	11-13 years (N=186)	14-17 years (N=153)	4-5 years (N=88)	6-10 years (N=364)	11-13 years (N=186)	14-17 years (N=187)	4-17 years (N=1,583)
Sleeping (min/day)	581.40 (45.22)	542.51 (40.00)	509.46 (50.56)	480.92 (60.18)	587.29 (34.68)	550.85 (37.32)	513.01 (58.49)	501.17 (69.94)	530.62 (57.54)
Lying (min/day)	217.15 (62.64)	227.59 (82.97)	262.52 (105.52)	252.53 (105.28)	191.75 (60.75)	197.68 (70.42)	235.39 (86.35)	207.01 (89.91)	223.21 (87.90)
Sitting (min/day)	313.27 (51.31)	342.89 (60.88)	391.33 (92.24)	432.16 (101.45)	322.20 (44.36)	368.94 (59.85)	398.67 (71.13)	441.25 (91.38)	378.78 (83.08)
Standing (min/day)	99.28 (23.60)	98.60 (27.99)	84.84 (32.82)	105.28 (40.60)	123.37 (32.42)	115.84 (27.42)	116.89 (30.72)	134.95 (43.97)	109.45 (35.42)
Moving (min/day)	97.15 (17.50)	88.00 (17.09)	69.99 (19.12)	64.26 (21.66)	97.01 (15.63)	85.89 (16.34)	69.28 (18.00)	59.72 (17.01)	78.51 (21.45)
Slow walking (min/day)	39.33 (12.53)	43.59 (19.05)	40.56 (15.91)	28.54 (19.22)	36.84 (9.37)	37.32 (13.92)	36.31 (12.35)	19.82 (16.59)	36.09 (17.39)
Other (min/day)	5.17 (4.00)	2.61 (2.59)	1.33 (2.57)	0.70 (1.30)	4.80 (3.88)	2.37 (2.91)	0.94 (1.74)	0.74 (1.54)	2.05 (2.85)
Fast walking (min/day)	35.28 (9.05)	49.22 (19.04)	47.44 (18.35)	53.28 (22.65)	33.49 (9.02)	43.98 (15.27)	44.58 (16.60)	54.30 (21.33)	46.70 (18.58)
Cycling (min/day)	13.85 (7.86)	8.32 (9.54)	6.81 (12.26)	6.77 (8.17)	11.34 (6.43)	8.11 (6.87)	6.70 (8.96)	6.92 (9.50)	8.03 (9.09)
Stair walking (min/day)	16.18 (5.50)	15.61 (5.58)	11.69 (5.61)	8.20 (4.11)	13.62 (4.48)	12.87 (4.21)	9.83 (4.34)	7.33 (3.32)	12.06 (5.5)
Running (min/day)	16.26 (6.74)	15.14 (7.58)	8.36 (6.70)	4.66 (4.66)	14.36 (5.84)	11.47 (6.39)	5.33 (4.19)	3.07 (4.56)	9.92 (7.63)
Steps (count/day)	14,003 (3523)	15,725 (3828)	12,958 (4044)	10,856 (3616)	12,805 (2837)	13,315 (2934)	11,362 (3191)	9,723 (3080)	12,907 (3,918)
Non-Wear Time (min/day)	5.68 (12.27)	5.94 (12.06)	5.66 (12.15)	2.71 (7.57)	3.94 (9.65)	4.67 (10.91)	3.09 (7.72)	3.72 (10.56)	4.58 (10.73)
Sedentary behavior (min/day)	530.42 (57.82)	570.47 (69.07)	653.86 (70.42)	684.69 (84.00)	513.94 (57.57)	566.62 (60.64)	634.06 (66.49)	648.26 (75.76)	530.62 (57.54)
Light physical activity (min/day)	240.68 (40.80)	232.61 (47.14)	196.61 (50.46)	198.67 (59.36)	261.86 (44.42)	241.28 (42.78)	223.36 (47.52)	215.16 (58.29)	225.96 (52.16)

Moderate-to-vigorous physical activity (min/day)	81.83 (21.16)	88.47 (24.54)	74.41 (27.51)	73.01 (28.38)	72.96 (18.22)	76.58 (21.35)	66.49 (22.44)	71.69 (26.08)	76.84 (25.06)
Physical activity level	1.47 (0.10)	1.47 (0.10)	1.39 (0.11)	1.37 (0.10)	1.44 (0.08)	1.43 (0.09)	1.37 (0.09)	1.36 (0.10)	1.42 (0.11)
WHO 2010 guideline fulfillment (%)	29.87	36.26	15.51	8.50	18.18	19.78	10.75	13.90	20.4
WHO 2020 guideline fulfillment (%)	83.12	88.01	66.84	64.71	77.27	79.40	61.83	63.64	74.5

155 Sleeping

156 Children and adolescents in older age-groups slept significantly less than those in younger age-groups for both
157 sexes. Girls slept significantly more than boys in both the 6–10 and 14–17-year age groups (see Fig. S1D). Data
158 distribution shows more variance in older age groups, especially for girls.

159 Sedentary behavior

160 Total SB of participants was significantly higher in each successive older age group for both sexes. Boys
161 accumulated significantly more sedentary minutes than girls in the 11–13 and 14–17-year age groups (see Fig.
162 1a). Data distribution shows more variance in older age groups, especially for boys.

163 Subcomponents of Sedentary Behavior

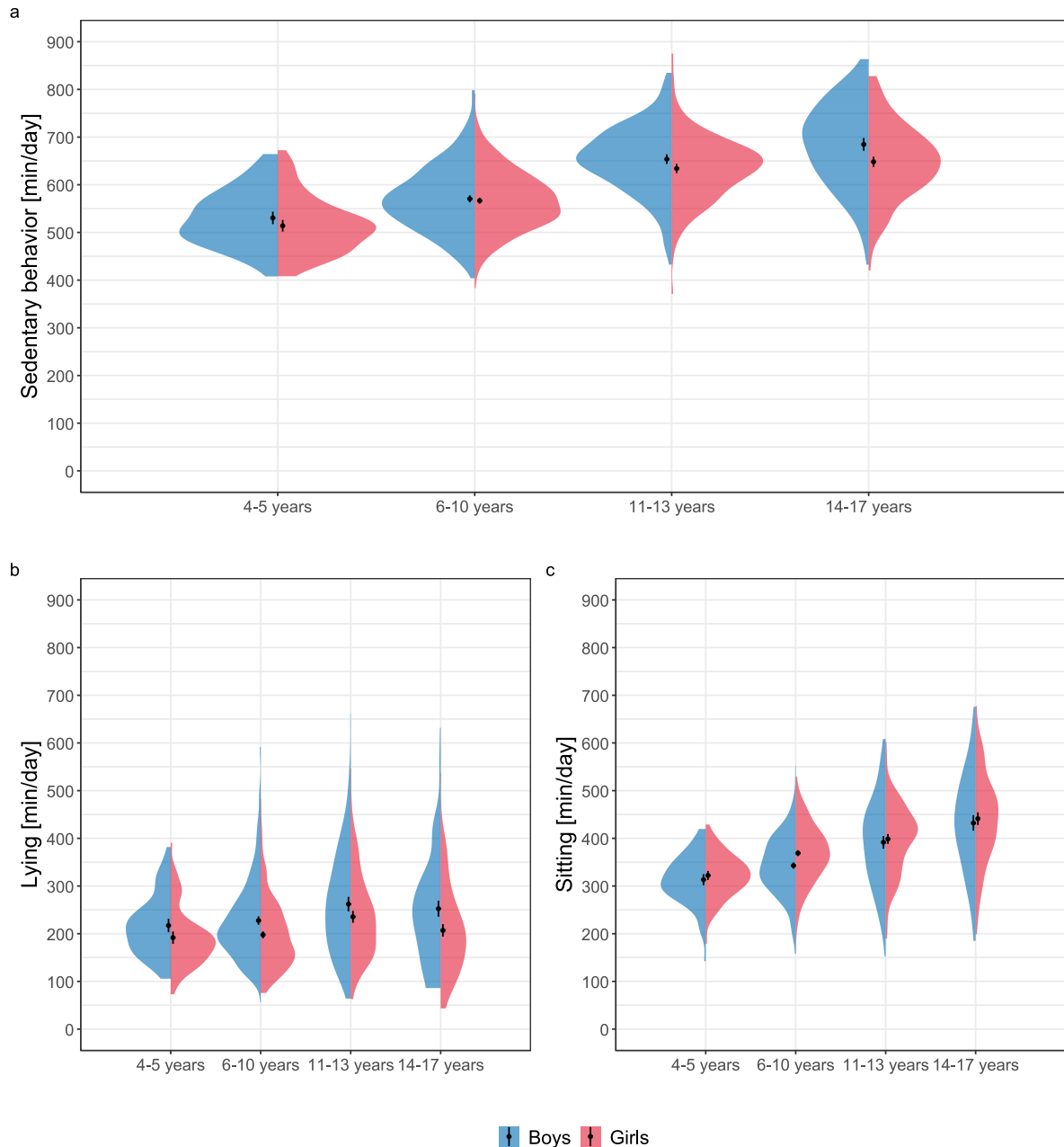
164 Lying (during wake time):

165 Lying time was significantly higher in the 11–13-year age group compared to the younger age groups for both
166 sexes. Among boys, lying time was significantly higher in the 11–13 and 14–17-year age groups compared to the
167 4–5 and 6–10-year groups. In girls, lying time was significantly higher in the 11–13-year group compared to all
168 other age groups. Across all age groups, boys exhibited higher lying times than girls (see Fig. 1b). Data
169 distribution shows more variance in 11-13 and 14-17 age groups.

170 Sitting:

171 Sitting time was significantly higher in older age groups for both sexes. Girls had significantly higher sitting
172 times than boys in the 6–10-year age group (see Fig. 1c). Data distribution shows more variance in 11-13- and
173 14-17-year age groups especially in boys.

174 Fig 1. Sedentary behavior time (a) and its sub behaviors lying (b), and sitting (c) stratified by sex and age group
175 visualized as the means, CIs, and density plots.



176

177 Light physical activity

178 LPA decreased between the age groups for both sexes. In girls, LPA was significantly lower in the 6–10
 179 compared to the 4–5-year age group, and in the 11–13 compared to the younger age groups. Among boys, LPA
 180 was significantly lower in the 11–13 and 14–17-year groups compared to the 4–5 and 6–10-year groups. Overall,
 181 girls demonstrated higher LPA than boys across all age groups (see Fig. S2D). Data distribution differs for 6–10-
 182 year-old girls and 11–13-year-old boys compared to the other age groups.

183 Subcomponents of light physical activity

184 Standing:

Standing accounted for the highest minutes per day among LPA behaviors. Boys in the 11–13-year group had lower standing time compared to other age groups, while girls in the 14–17-year group had higher standing time than younger girls. Girls consistently showed higher standing times than boys across all age groups, with differences ranging from 17.24 to 31.95 minutes per day (see Fig. S3D). Data distribution shows more variance in the 14-17 age group.

Moving (without purposeful walking):

Time spent moving decreased significantly between the age groups for both sexes. A significant sex difference was observed in the 14–17-year group, where girls spent fewer minutes moving per day than boys (see Fig. S4D). Data distribution shows comparable variance in all age groups.

Slow walking:

Boys in the 6–10 and 11–13-year groups had significantly higher slow walking times compared to the 4–5-year group, while the 14–17-year group had the significantly lowest values. Girls showed significantly lower slow walking times only in the 14–17-year group compared to younger groups. Significant sex differences were present in the 6–10, 11–13, and 14–17-year groups, with girls recording lower values than boys (see Fig. S5D). Data distribution shows less variance in the youngest age group and a positively skewed distribution in the oldest age group.

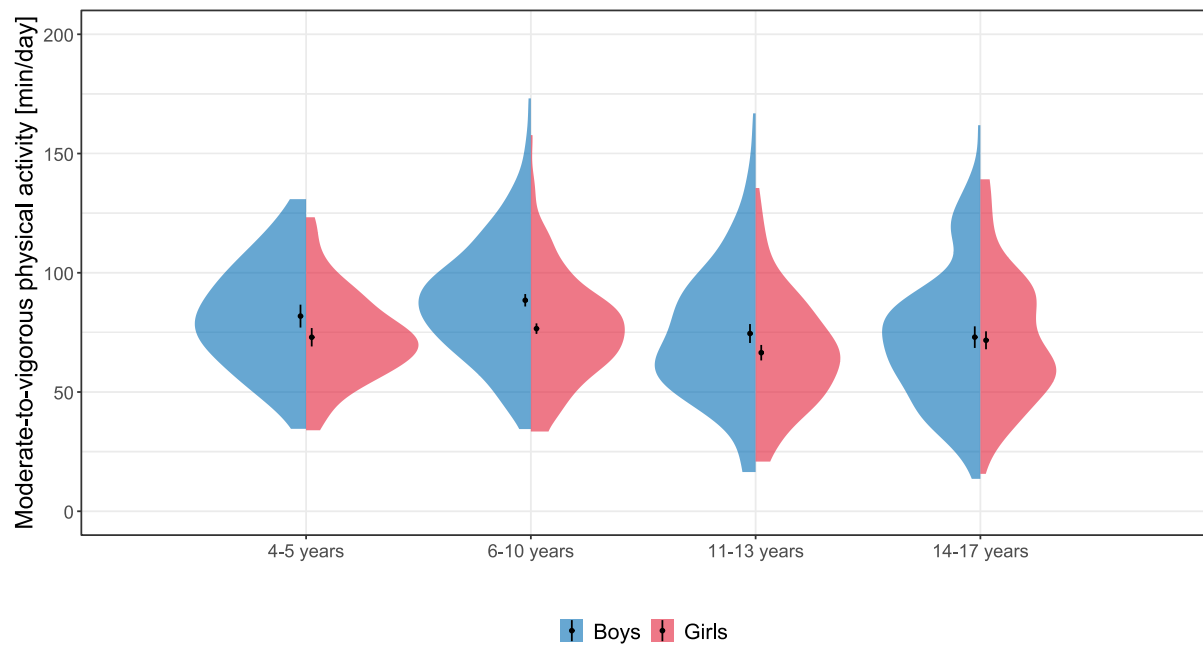
Other (non-classifiable movements):

Minutes per day classified as "other" were low and decreased significantly across age groups with no significant sex differences (see Fig. S6D). Data distribution shows less variance and a positive skew in older age groups.

Moderate-to-vigorous physical activity

In boys, MVPA was significantly highest in the 6–10-year group, followed by the 4–5-year group, and lowest in the 11–13 and 14–17-year groups. Among girls, MVPA was significantly lower in the 11–13-year group compared to other age groups. Boys exhibited significantly higher MVPA than girls in all age groups except for 14–17 years (see Fig. 2). Data distribution was different in the 14–17-year age group including a second lower peak.

Fig 2. Moderate-to-vigorous physical activity time stratified by sex and age group visualized as the means, CIs, and density plots.



212

213 Subcomponents of moderate-to-vigorous physical activity

214 Fast walking:

215 Walking fast was significantly lowest in the 4–5-year group, increased in the 6–10 and 11–13-year groups, and
 216 peaked in the 14–17-year group for both sexes. The only significant sex difference was in the 6–10-year group,
 217 where boys had higher values than girls (see Fig. S7D). Data distribution shows more variance in older age
 218 groups.

219 Cycling:

220 Cycling was most prevalent in the youngest age group followed by 6-10-year age group, and significantly lowest
 221 in the 11–13 and 14–17-year groups for both sexes. A significant sex difference was observed in the 4–5-year
 222 group, with boys cycling more than girls (see Fig. S8D). Data distribution shows a positive skew in older age
 223 groups.

224 Stair walking:

225 The significantly highest stair walking times were observed in the 4–5 and 6–10-year groups, followed by the
 226 11–13 and 14–17-year groups for both sexes. Boys had significantly higher stair walking times than girls across
 227 all age groups (see Fig. S9D). Data distribution shows less variance in older age groups.

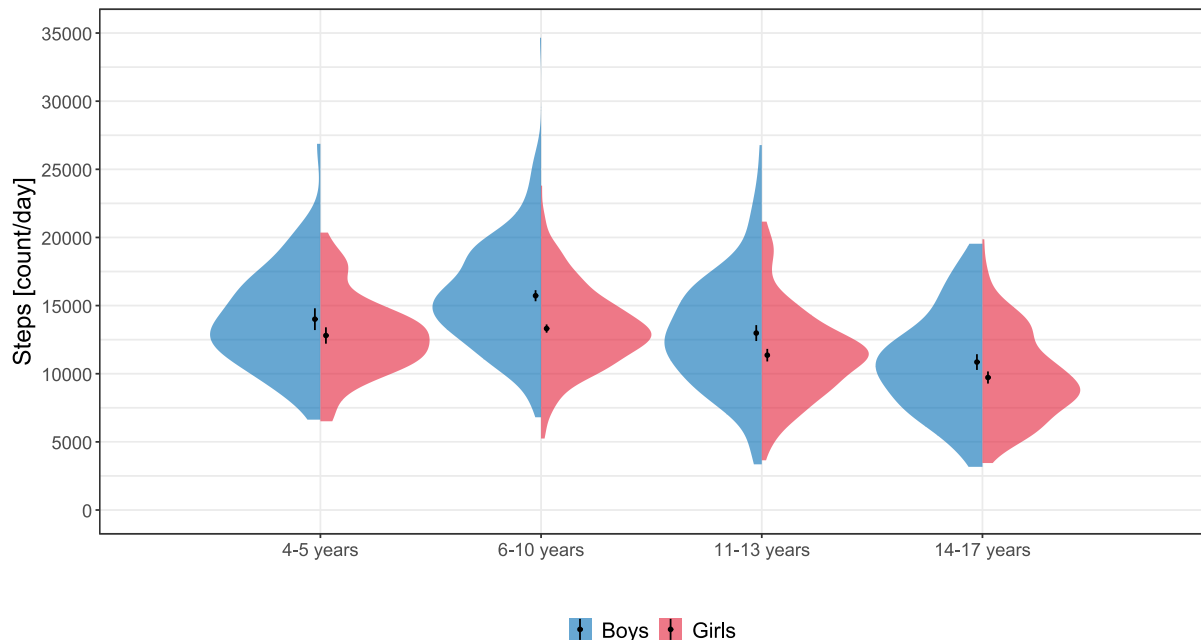
228 Running:

229 Running significantly decreased between the age groups, with 14–17-year-olds running only half as much as 4–
 230 5-year-olds for both sexes. Boys ran more than girls in all age groups except for the 4–5-year group (see Fig.
 231 S10D). Data distribution shows less variance and a positive skew in older age groups.

232 Steps

The significantly highest step counts were recorded in the 6–10-year group, followed by the 4–5, 11–13, and 14–17-year groups for both sexes. Boys consistently accumulated significantly more steps than girls across all age groups, with the largest difference observed in the 6–10-year group (see Fig. 3). Data distribution shows comparable variance throughout all age groups.

Fig 3. Step count stratified by sex and age group visualized as the means, CIs, and density plots.



Physical Activity Level

The Physical Activity Level was significantly higher in the 4–5 and 6–10-year groups compared to the 11–13 and 14–17-year groups for both sexes. Boys had significantly higher Physical Activity Level values than girls in the 6–10 and 11–13-year groups (see Fig. S11D). Data distribution shows comparable variance throughout all age groups.

World Health Organization physical activity guidelines

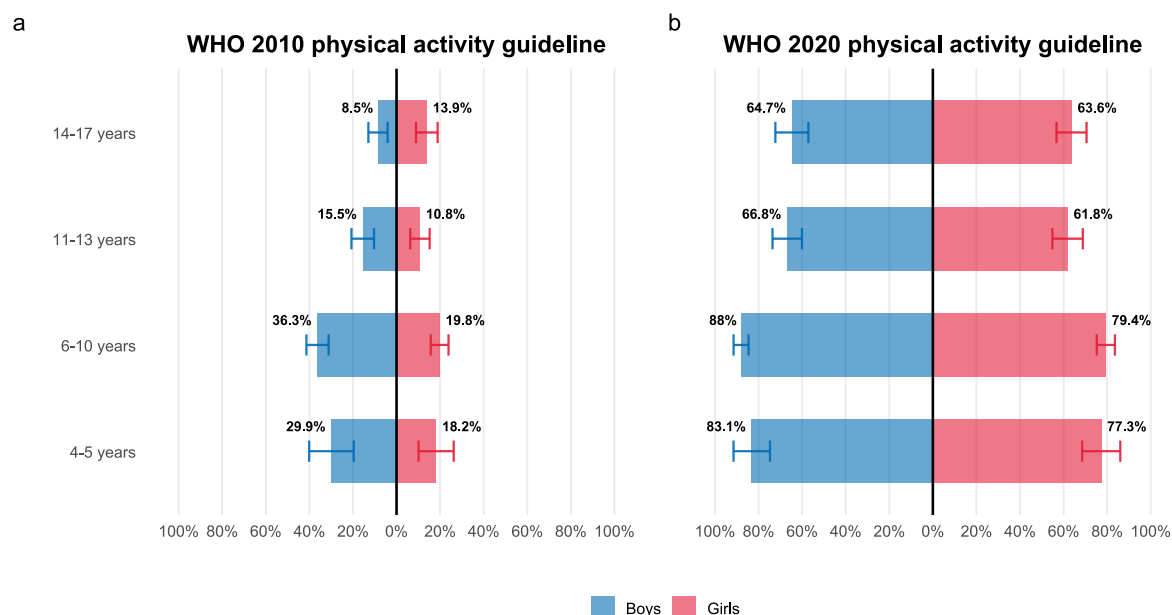
2010 WHO Guideline:

Boys had significantly higher rates of guideline fulfillment in the 4–5 and 6–10-year groups compared to the 11–13 and 14–17-year groups. Among girls, only the 6–10-year group showed significantly higher fulfillment compared to the 11–14-year group. A significant sex difference was observed in the 6–10-year group, with boys achieving higher guideline fulfillment than girls (see Fig. 4a).

2020 WHO Guideline:

Fulfillment was significantly higher in the 4–5 and 6–10-year groups than in the 11–13 and 14–17-year groups for both sexes. The only significant sex difference was in the 6–10-year group, where boys had higher fulfillment than girls (see Fig. 4b).

Figure 4. Sex and age-specific descriptive results for adherence to a) 2010 and b) 2020 WHO guideline fulfillment.



Discussion

This population-based cross-sectional study explored sex- and age group specific 24-h PBs, intensity categories, step count, WHO guideline fulfillment, and physical activity levels in a nationwide sample of children and adolescents living in Germany. Clear age- and sex-specific patterns were observed across PBs, intensity categories, and additional outcome variables. Older age groups consistently exhibited less time in sleep and PA, and more time spent in SB. Boys exhibited higher SB and MVPA, while girls had higher LPA and sleep duration in specific age groups. Adherence to WHO PA guidelines was highest in younger children and declined with age, with boys more likely to meet guidelines than girls, particularly in the 6–10-year group. PBs showed distinct patterns compared to intensity categories with boys e.g. spending less time sitting but more overall SB than girls.

Time spent in the different intensities of the 24-hour PB cycle differed in the current sample compared to the pooled results of Kuzik and colleagues²⁵ that included the same age range as the MoMo 2.0-Study. Participants in our study slept around 15 minutes less, were 67 minutes more sedentary, had 82 minutes less LPA, and 17 minutes more MVPA than in the meta-analysis of Kuzik and colleagues²⁵. This result is comparable to another pooled study including 9-11 year old children from 12 countries²⁶. Here, participants in our study reported comparable sleep measures with differences of -48 to 23 minutes. SB was 29 to 116 minutes higher, LPA 67 to 119 minutes lower, and MVPA 8 to 34 minutes higher in our sample. This result can be expected, as the studies included in the meta-analysis used accelerometers on the waist, wrist or back and self-reported estimates, and the pooled study applied hip-worn accelerometry, different epoch lengths, and algorithms for the intensity categories which influences the overall minutes spent in the different intensities^{6,7}. Giving the high validity of thigh worn accelerometers for the detection of SB⁹, and the large descriptive differences in SB, the SB results of the two pooled studies^{25,26} might be underestimating the SB of children and adolescents in favor of LPA in addition to country and sample specific peculiarities. Comparing our results to another study that employed lower-back and thigh worn accelerometers and report on a cohort of 8 year olds from New Zealand¹², the 6-10 year age group in

our study slept 26 minutes less, had 120 minutes more SB, and had 84 minutes less LPA, and 16 minutes less MVPA. The main difference between the studies is, that Hedayatrad and colleagues¹² applied a cut point based approach based on the lower back sensor, while the current study relied on PB classification from the thigh worn sensor followed by intensity categorization which again could explain the large differences regarding SB that might go beyond differences in the samples. Regarding the PBs reported, the study of Hedayatrad and colleagues¹² used both lower back and thigh data and did not account for waking hours so only standing, walking, and running are comparable. Here, 6–10-year-old participants in our study stood 48 minutes less, walked 19 minutes less, and ran twice as much (6 minutes more). To differentiate the methodological influences from the results, a reassessment of the before mentioned study data would be necessary, emphasizing the need for transparent reporting and open-source algorithms to enable future pooled studies.

The 2020 WHO guideline fulfillment of this study is lower than in the study of Hedayatrad¹² from New Zealand, who report 90% guideline fulfillment but higher than reported by other accelerometer studies like the 29.9% based on waist-worn accelerometers employing 60 second epochs and cut point analyses in 3 to 18 year olds from the International Children's Accelerometry Database²⁷. The umbrella review of Kracht and colleagues²⁸ that focusses on 24-hour guideline fulfillment found that around half of children met the PA guideline part. The differences in guideline fulfillment can again be partially contributed to methodological choices i.e. wear-position, epoch-length, and algorithm/ cut point of choice, and wear time peculiarities in the studies. E.g. the shorter the epoch length, and the longer a device is worn on the day, the higher the potential to detect MVPA minutes⁶. The large discrepancies between the 2020 and 2010 guidelines have been described before with a guideline fulfillment of 5.3% for the 2010 and 29.9% for 2020 WHO guideline²⁷. The same pattern was found by a study on the previous MoMo waves that found a guideline fulfillment of 4.4% for the 2010, and 32.0% for the 2020 guideline in 6- to 17-year-olds employing hip worn accelerometers²⁹. As with the current data, the 2010 guideline fulfillment showed higher age- and sex differences than the 2020 guideline fulfillment and the large differences in prevalence can be attributed to different wear-time and data processing procedures. This finding is unsurprising, given that the WHO 2020 recommendations can be satisfied in numerous ways for children and adolescents, such as accumulating the weekly average of 60 minutes per day through a single prolonged session of seven hours on one day. By contrast, compliance with the WHO 2010 guidelines requires children and adolescents to complete at least 60 minutes of moderate-to-vigorous PA on each day of the week. The WHO PA guidelines released in 2020 expand on the 2010 recommendations by reiterating that all amounts of PA are beneficial, that higher levels are associated with greater health benefits, and by newly addressing the need to limit sedentary behavior.

Sex and cross-sectional age group differences found by this study are comparable to previous studies. As children grow older, their sleep duration decreases and SB, particularly sitting, increases^{30–32}. PA is lower and SB higher in older participants³³ which was also confirmed by longitudinal studies e.g.³⁴ and emphasizes the need for effective interventions buffering this effect caused by changing habits and preferences in youth especially during transitional phases from early childhood to childhood and adolescence³⁵. Sex differences were also reported by previous studies showing that boys have higher MVPA values and WHO guideline fulfillment³³ but lower LPA and standing time than girls¹² while other studies found no sex difference in LPA³⁶. Differences for SB are less clear with some studies reporting higher SB in girls³⁶ contrasting our findings while others found higher SB in boys overall³⁷ or for the older age groups³³.

The current study expands previous findings by distinguishing these intensity categories differences at the behavioral level.

The difference in SB is attributed to boys spending more time lying down, while girls spend more time sitting, though this difference is less pronounced. These patterns suggest opportunities for sex-specific interventions.

The higher LPA minutes in girls can be attributed to increased standing time, which offsets the higher time boys spend moving and walking slowly pointing to a need to evaluate the discrepancy between standing and other active LPA behaviors regarding health benefits.

For MVPA, boys demonstrate higher values across all subcategories, but these differences vary by age group. Boys show higher values than girls for walking fast in the 6–10-year old group, higher cycling times in the 4–5-year olds, higher stair-walking times across all age groups except the 14–17-year olds, and higher running times except in the 4–5-year old group. This results in overall higher MVPA in all age groups, except for the 14–17-year olds, and highlights the benefit of differentiating intensity categories into distinct behaviors. One possible strategy could be to promote different behaviors in various age groups for girls if the goal is to achieve a similar overall MVPA value compared to boys. Moving beyond mean values, the distributions of outcomes indicate that both variance and skewness of PB and PA intensities increase with age, with distinct sex-specific patterns emerging for both sedentary and physically active behaviors. The most pronounced finding was observed in the MVPA distribution among the 14–17-year-old group, which exhibited a possible bimodal pattern with a secondary lower peak, suggesting the emergence of distinct subgroups of highly active and less active adolescents. Subcomponents of MVPA, such as cycling, running, and slow walking, displayed positively skewed distributions in older age groups, with most participants accumulating little or no time in these activities and a minority engaging at much higher levels in these behaviors.

Step counts showed relatively stable variance across age groups, with boys consistently accumulating more steps than girls as reported in other studies ^{33,38}. The total step count in our study was higher for the age groups 4-5 and 6-10 years and comparable for the age groups 11-13 and 14-17 compared to a systematic review on step counts from pedometer studies ³⁸ and overall higher but with a similar age pattern compared to other studies ³³. The PAL based on 24-h PB is comparable to previous studies following different estimation approaches ³⁹ which adds to its plausibility in this study.

Perspective

The results of this nationwide study provide valuable orientation by extending beyond conventional intensity categories to include fundamental PBs. By adopting a 24-hour paradigm, the study advances beyond previous MoMo waves that primarily focused on PA alone, thereby enabling future analyses of the co-dependencies between sleep, SB, and PA across the entire day. The distinct patterns observed for specific behaviors compared with the broader intensity categories in which they are embedded, together with sex- and age-specific findings, underscore the value of greater differentiation in accelerometry studies. Incorporating context-specific time windows derived from participant diaries and using higher-resolution data represent important next steps toward a better understanding of PB patterns in children and adolescents.

Strengths and limitations

This study comes with some strengths and limitations. First, the accelerometer sample differs from the nationally drawn sample of the MoMo 2.0-Study, limiting generalizability. Nevertheless, this study offers valuable insights into a large sample of children and adolescents within a broad age range in Germany. Second, using weekly averages is useful to display overall patterns of PB but time and day-specific peculiarities remain hidden with this approach. Further in-depth analysis of the MoMo 2.0 -Study accelerometry data will be conducted in the future. Third, the results are tightly linked to the methodology used for the wear protocol and data processing of accelerometer data. With the chosen approach of analyzing thigh-worn accelerometer data from only one device with ActiPASS it is for example challenging to distinguish between lying and sitting ⁹. Therefore, the results within SB have to be treated with caution. This is however the case in all accelerometer studies and the transparent reporting and open access algorithms in this paper help the correct interpretation of the results. However, this study offers a detailed documentation and transparent reporting of the accelerometer assessment and its data processing to enable better comparison between other accelerometer-based studies. Finally, the compliance rate of this study should be acknowledged as a limitation and considered when setting up studies to end up with the required sample size.

Conclusion

The present population-based cross-sectional study demonstrated distinct age- and sex-specific patterns in 24-hour PBs, intensity categories, and adherence to WHO PA among children and adolescents living in Germany. SB increased with age while sleep duration and overall PA declined, with boys exhibiting higher levels of SB and MVPA, and girls demonstrating higher LPA and sleep duration in specific age groups. Adherence to WHO PA guidelines decreased progressively with age, and boys were more likely to meet recommended activity levels than girls. Importantly, differentiating between PB categories and intensity levels in accelerometry-based research provided additional insight into the complex interplay of movement behaviors, underscoring the value of higher methodological differentiation in youth PA surveillance. These findings may serve as a reference for future intervention studies and public health strategies targeting age- and sex-specific promotion of health-enhancing behaviors in children and adolescents.

Abbreviations

MoMo = Motorik Modul

MVPA = moderate-to-vigorous physical activity

PA = physical activity

PB = physical behavior

SB = sedentary behavior

WHO = world health organization

Declarations

Ethics approval and consent to participate

390 All procedures performed in studies involving human participants or on human tissue were in accordance with
391 the ethical standards of the Institutional Research Committee and with the Declaration of Helsinki of 1975 and
392 its subsequent amendments or comparable ethical standards. Ethical approval for the MoMo 2.0-Study was
393 obtained from the Ethics Committee of the Karlsruhe Institute of Technology on 6 November 2023 (application
394 number A2023-077). Informed consent was provided by legal guardians or participants (for those over 15 years).

395 Consent for publication

396 Not applicable.

397 Availability of data and materials

398 The dataset is subject to access restrictions to ensure data protection and compliance with ethical standards.
399 Access can be granted upon a justified request and after signing a data use agreement. Requests should be
400 addressed to the principal investigator of the MoMo 2.0-Study. Each request will be reviewed individually to
401 ensure that the proposed use is consistent with the study's objectives and ethical guidelines.

402 Statistical analyses were performed using R and RStudio (R Core Team, 2025; RStudio Team, 2025). The code
403 used to generate the study results is available upon reasonable request from the corresponding author. Please note
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405 Competing interests

406 None declared

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412 Author contribution

413 Conceptualization: AB, BHM; Methodology: AB, BHM; Data curation and formal analysis: JF, SK, MF;
414 Investigation: AF, LT, CZ, LK, SK; Writing - original draft preparation: JF; Writing - review and editing: JF, AB,
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