

Comparing Physical Activity Metrics From Different Placements of Thigh-Worn Accelerometers

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Background: Compared with other placements, thigh-worn accelerometers offer the advantage to accurately capture postures. However, the lack of standardized sensor placement on the thigh raises concerns about the comparability and harmonization of data across studies. This study aimed to investigate the impact of sensor placement on thigh-worn accelerometer measurements. **Methods:** Thirty-six participants wore two sensors simultaneously at center- and upper-thigh position on the same thigh during daily activities for several days. Metrics of vector magnitude (Euclidian Norm Minus One), postures, and activities generated by GGIR and ActiPASS were analyzed with Bland–Altman plots and linear regressions. **Results:** The findings revealed a significant dependence of vector magnitude on sensor placement: 1 cm higher distance between the center- and upper-thigh position was correlated with almost 1 mg higher difference in Euclidian Norm Minus One between the two positions ($b = 0.94$; 95% confidence interval [0.26, 1.62]). For time spent sedentary ($b = 0.03$; 95% confidence interval [−2.48, 2.55]) and intense physical activities ($b = 0.22$; 95% confidence interval [−0.10, 0.54]), the sensor position had no significant effect on the results. High concordance was also observed for other activities, such as walking, running, and sleeping. **Conclusions:** The analyses suggest that, despite variations in sensor placement, thigh-worn accelerometry data can be compared and harmonized for most postures and activities when analyzed by ActiPASS. The robust metrics by ActiPASS to accelerometer placements is likely because it utilizes multiple features in the acceleration signal (e.g., inclination, rotation) to classify activities and postures, rather than relying on a single feature (vector magnitude).

Keywords: validation, activity classification, sedentary behavior, vector magnitude

The measurement of physical activity by accelerometers offers great advantages compared with other activity assessments such as questionnaires and diaries, notably a detailed recording of the full 24-hr daily cycle. Combined with suitable and reliable software that transforms the acceleration signals into meaningful metrics, the device measurement of physical behavior offers a high potential for health research and surveillance (Troiano et al., 2020).

The Prospective Physical Activity, Sitting, and Sleep consortium (ProPASS) is working on guidelines and tools to harmonize existing and future accelerometer studies, aiming at pooling the data from different cohorts and countries to further increase the potential of the device-based measurement of physical activity (Stevens et al.,

2020). ProPASS proposed a 24/7 construct of physical behaviors with five dimensions: intensity, posture/activity type, bout duration, domain (work/non work), and biological state (sleep/wake; Stevens et al., 2020). To attain information according to this 24/7 construct, ProPASS applied thigh-worn accelerometer placement with the custom-made software ActiPASS (Hettiarachchi & Johansson, 2023). ProPASS has chosen thigh placement due to the possibilities of detection of postures and activities (Stamatakis et al., 2020).

In hip and wrist placement, the positioning of accelerometers is often very well defined by using a bracelet or a hip belt. At these sites, activity intensity is typically assessed solely through acceleration (vector magnitude). The disadvantage with thigh-worn accelerometers is that placement is not as well defined. Theoretically, positioning the accelerometer closer to the knee would result in an increase in total acceleration, hence in a higher vector magnitude. Therefore, we hypothesize that it is not suitable to use vector magnitude on thigh-based measurements if the exact location on the thigh is not harmonized. By placing the accelerometer on the thigh, the activities can be classified into different behaviors without taking the total acceleration into account. To estimate intensity, ActiPASS relies on behavior, that is, activities and postures, and cadence. Nonetheless, the influence of thigh placement on cadence-based measures (e.g., in ActiPASS) and vector magnitude-based measures remains undetermined.

Although there were no ex-ante harmonization of accelerometer studies before the establishment of ProPASS, most study protocols of thigh-worn accelerometer assessments instructed to place the sensors approximately at the mid of the (front) thigh (Stevens et al., 2020). Thus, sensor data collected by these studies might be considered comparable, and thus appropriate to harmonize.


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First analyses using harmonized data from different cohorts has been published (Ahmadi et al., 2024; Blodgett et al., 2024) with more cohorts being continually included. However, the placement of the accelerometer on the thigh can differ between the studies, and there might be deviations in the exact placement between individuals as finding the midpoint of the thigh is not obvious (e.g., the midpoint might be estimated differently while standing or sitting). This might be especially relevant in studies where participants attach the accelerometer themselves, compared with trained interviewer or nurses, as variations in individual interpretation and application of the instructions could lead to inconsistencies in device placement. There are also study protocols of thigh-worn accelerometers that instruct other placements on the thigh. A review of studies using thigh-worn activPAL devices showed that the placement positions mostly vary between the mid-thigh and upper thigh, with some studies not reporting the exact placement (Edwardson et al., 2017). In ProPASS, the Survey of Health, Aging and Retirement in Europe (SHARE) is a cohort in which participants were asked to wear the accelerometer at the upper thigh (Scherpenzeel et al., 2021).

The aim of this study was to investigate the influence of the sensor's position on the thigh on different activity metrics, namely the vector magnitude—calculated as Euclidian Norm Minus One (ENMO) using the software GGIR (see section “Data Processing”)—and postures and activities identified by ActiPASS. Therefore, we used data from participants who wore two sensors simultaneously on the same thigh during daily living. We hypothesized: (a) that the vector magnitude is systematically higher at the mid-thigh compared to the upper thigh position. This would indicate that metrics relying solely on movement, that is, vector magnitude, are not suitable for varying thigh placements. (b) that the postures and activities identified by ActiPASS, which incorporates both movement and angles, would remain unaffected by the sensor's position on the thigh.

Methods

Data

Data from the Thigh Accelerometry Position Study (TAPS; Franzese, 2023) were used to investigate the influence of positioning of accelerometers on the results of analysis software. TAPS was conducted in Germany from April to May 2023 with a nonprobability convenience sample of 36 voluntary adults. Two accelerometers (type “Axivity AX3;” 50-Hz sampling frequency; $\pm 8 g$ range) were worn simultaneously on the same thigh (center and upper thigh) during everyday activities for 7 days (from midnight to midnight). Participants were instructed to place the devices “on the upper half of the front side of your thigh” and “at the center of the front side of the same thigh” without any further specification. The participants attached the accelerometers themselves using medical adhesive tape (type “Opsite Flexifix”) and a gauze pad that was placed between the skin and the device. Participants filled in a short questionnaire including questions on the exact position of the devices in relation to the top of the patella when standing up, which should be measured using a measuring tape. Participants wore the accelerometers during daily living; however, to increase the incidence of relatively rare activities like running, cycling, and stair walking, participants were encouraged to perform these activities during the measurement period. The data, the instructions for participants, and the questionnaire are available online (Franzese, 2023). The TAPS study was approved by the ethics council of the Max Planck Society (Germany).

Data Processing

The raw accelerometer data was processed with GGIR (Migueles et al., 2019) and ActiPASS (Hettiarachchi & Johansson, 2023) to generate various metrics on daily level. GGIR is an open-source R package to analyze accelerometer sensor data. GGIR (version 3.0.0; Migueles et al., 2019)—default settings including auto calibration (van Hees et al., 2014), run with R version 4.3.2 (R Core Team, 2023)—was used to generate the average acceleration in terms of ENMO. To calculate ENMO, the measurements of all three axis (x , y , and z) were combined into one vector and $1 g$ is subtracted to cancel out gravity ($\sqrt{x^2 + y^2 + z^2} - 1$), negative values are rounded to zero (van Hees et al., 2013). ENMO can be used to describe the volume of activity and is denoted in milligravity (mg). ENMO describes the average acceleration in a defined time period, which can be interpreted as volume of activity and is used as basis for other metrics, for example, intensity gradient, and cut-point based classification of light, moderate, and vigorous activities (Rowlands et al., 2019).

ActiPASS is an activity recognition software for thigh-worn accelerometer data, with its source code openly available and a compiled version provided upon request free of charge (Hettiarachchi & Johansson, 2023). The ActiPASS software is based on the activity detection algorithm Acti-4 (Skotte et al., 2014) that is proofed to detect various activities such as sitting, standing, walking, stair walking, bicycling, and running (Skotte et al., 2014; Stemland et al., 2015). Furthermore, algorithms to detect lying down and sleep has been implemented in the ActiPASS software (Hettiarachchi et al., 2021; Johansson et al., 2023). The Acti-4 algorithm is based on a decision tree. The important parameters in this decision tree are the inclination of the thigh with respect to gravity (both absolute and forward/backward angles), and the SD of the acceleration (both in vertical direction and also the maximum direction). A validation study has showed that the Acti-4 algorithm is robust for different accelerometer brands (Crowley et al., 2019). In this study, three different sensors were placed simultaneously on different positions on the thigh (mid-thigh, below and above). However, it could not conclude on differences between the positions, as the sensors' order was randomized and the influence of the position was not systematically investigated.

Measures provided by ActiPASS (version 1.61 Beta; Hettiarachchi & Johansson, 2023) include daily time spent in different activities, such as walking, running, sitting, lying, cycling, sleeping, as well as detected number of steps and transitions between sit/lie and any upright posture. “Sedentary” is defined as lying or sitting during wake time. The activities may be grouped into different intensity classes. Intensive activities are defined as the time “running,” “cycling,” “stair walking,” “walking” (with a cadence above 100 steps/min) and “other” with periodic movements with a cadence of 100 steps/min and higher. Walking is categorized as slow with a cadence below 100 steps/min, and fast with a cadence of 100 or more steps/min. The category “move” is defined as periods with standing posture and movements above the threshold for standing, but no purposeful walking. In somewhat simplified terms, “sleeping” was defined as the time from the first instance when the sleep algorithm (Johansson et al., 2023) identified sleep to the last time it identified wakefulness, within the two longest consecutive periods of lying down or sitting (with a weighted priority to lying periods and periods occurring within 22.00–08.00) during a 48-hr moving time window. Thus, the term “Sleeping” in this article corresponds to the construct “Sleep interval” (Ibáñez et al., 2018) normally occurring every 24 hr.

Covariates

Participant's age (years), gender, and height (in centimeters) are available from the TAPS questionnaire and were used as covariates in the multivariate analysis. Additional information from the questionnaire is the length of the respondent's thigh and the distance between the two devices (both in cm), measured by the respondent using a tape measure.

Statistical Methods

The metrics from both positions (center and upper thigh) were compared using equivalence tests (two one-sided tests; Lakens, 2017) and Bland–Altman plots to identify potential bias (Bland & Altman, 1986). An equivalence test is used to determine if two means are equivalent within a specified margin. We applied these tests using a $p = .05$ threshold for each test, resulting in a 90% confidence interval (CI). The acceptable difference (delta) between the two measures was defined as 5% of the mean of both, center, and upper position. Bland–Altman plots show the mean of the two measurements on the horizontal axis and the difference between the two measurements on the vertical axis. In this way, they show whether a higher value of the specific measure is associated with a higher or lower deviation between the two measures. The 95% limits of agreement (average difference ± 1.96 SD of the difference) as well as the absolute and relative range from lower limit to upper limit were investigated. To account for the structure of the data, that is, multiple observations (days) per participant, the limits of agreement were adjusted accordingly (Bland & Altman, 2007). In a next step, linear multivariate ordinary least squares (OLS) regressions were used to assess the importance of the exact placement, that is, the distance between the devices. The outcome variable was the difference in metrics between the two devices, with the predictors including the distance between them. Clustered SEs (by participant) were used to account for the nested data structure, that is, adjusting the SEs for the autocorrelation of error terms within (the multiple observations per) individuals (Thrane, 2020, pp. 91–92). All analyses were performed using Stata 17 (StataCorp., 2023).

Results

The TAPS data provide measurement from 36 participants, 31 of whom wore the sensors for 7 days. However, some days were not available for analysis due to device malfunctions and the exclusion of days with less than 20 hr of measurement. The final data set consists of 213 days of observation from 36 persons. For 25 of the participants (79%), all 7 days were available (mean = 5.9 days per participant, $SD = 1.9$). Table 1 describes the sample at the individual level. Sixty-one percent of the participants were female, and 39% were male. The mean age was 39 years ($SD = 11$) with a range of 26–72 years. Participants placed the devices on average 13.1 cm above the kneecap ($SD = 3.3$ cm; min. = 5 cm; max. = 20 cm). The distance between the devices ranged from 2.5 to 13 cm (mean = 7.3 cm, $SD = 2.3$ cm).

For the ENMO analysis, one participant (=7 days) was dropped because calibration of one device was not possible in GGIR. Most of the activities were detected by ActiPASS on all 213 days, with the exception of lying, running, cycling, and “other” which were detected in at least one of the two positions on 208 days (of 36 participants), 192 days (of 36 participants), 115 days (of 33 participants), and 47 days (of 25 participants), respectively. Table 2 describes the metrics derived from GGIR and ActiPASS on a daily

Table 1 Descriptive Information of the Study Population

Variable	%	Mean	SD	Min	Max
Gender: Female	61				
Gender: Male	39				
Age (years)		38.72	11.13	26	72
Device gap (cm)		7.29	2.25	2.5	13
Height (cm)		172.19	9.42	155	194
Thigh length (cm)		46.15	4.01	36	55
Valid days		5.92	1.93	1	7

Note. Thigh accelerometry position study. $N = 36$ participants.

basis. To compare the aggregated metrics regarding their sensitivity for placement, Table 2 shows the relative differences between the two means. The relative difference for ENMO is 15.9%, which is much higher than the relative difference of all other metrics, for example, for Sedentary and Intense Activities, it is only 0.6% and 2.5%, respectively. Table 2 also includes an equivalence test (two one-sided tests) of the means from upper and center thigh with acceptable differences (delta) between the two measures defined as 5% of the mean. Applying the $p = .05$ threshold for each test (resulting in a 90% CI), the test revealed that the means can be considered as equivalent for the number of steps, time spent sedentary, Intense Activities, fast walking, walking, running, standing, sitting, and sleeping, and transitions. The means of ENMO, slow walking, walking stairs, cycling, move, “other,” and lying were not equivalent according to the defined delta.

Figure 1 shows Bland–Altman plots for ENMO as well as three commonly used metrics derived from ActiPASS, that is, the number of steps per day, time spent sedentary (minutes per day), and time spent in intense activity (minutes per day). The solid line represents the mean difference, indicated as a linear trend. The dashed lines indicate the 95% limits of agreement (mean difference ± 1.96 SDs). Bland–Altman plots for other postures and activities— that is, walking slow, walking fast, walking, running, walking stair, cycling, moving, “other,” standing, sitting, lying, sleeping, and number of transitions—are available in Appendix 1. Complementing information, including statistical tests of fixed bias and limits of agreement, is shown in Table 3.

Compared with other metrics, the Bland–Altman plot for ENMO looks quite scattered. This impression is confirmed by the last column in Table 3, which shows the range of limit of agreement (LoAR) relative to the mean (from center position). For ENMO, the LoAR of 110% indicates a low precision. The linear trend also indicates a systematic bias in a way that a higher mean is correlated to a higher difference between the two measures, which was confirmed as significant in the test for proportional bias ($\beta = 0.43$; 95% CI [0.31, 0.56]). Standardized coefficients and CIs are reported in Appendix 2.

The number of steps showed a proportional bias as well as the positive slope is significant ($\beta = 0.21$; 95% CI [0.08, 0.34]; see Appendix 2). However, the relative LoAR was much smaller for the number of steps (16%) compared to ENMO. While for time spent sedentary, and Intense Activities, the trend indicates a negative association, it is nonsignificant ($\beta = -0.06$; 95% CI [-0.20, 0.07] and $\beta = -0.09$; 95% CI [-0.23, 0.04], respectively). Also, compared with ENMO, the relative LoAR was much smaller for sedentary time (26%) and Intense Activity (23%). The fixed bias, that is, the mean of the differences between center- and upper-thigh position for number of

Table 2 Descriptive Information of the Daily Physical Behaviors When Measured With Accelerometer Places on Center and Upper Thigh on 36 Participants

Variables	Unit	N (days)	Center			Up			Equivalence test ²		
			Mean	SD		Mean	SD		Delta	p upper bound	p lower bound
Euclidian Norm Minus One ³	mg	206	28.04	13.51		23.57	10.37		1.29	1.00	.00
Number of steps	Number	213	11,500.62	5,611.31		11,241.41	5,511.19		568.55	.00	.00
Sedentary	Minutes	213	614.74	135.23		618.44	137.79		30.83	.00	.00
Intense activities	Minutes	213	93.06	45.90		90.77	46.40		4.60	.00	.00
Walk slow ⁴	Minutes	213	17.69	13.54		18.86	14.19		0.91	.00	.90
Walk fast ⁵	Minutes	213	69.23	33.24		66.16	33.06		3.38	.33	.00
Walk	Minutes	213	86.93	39.85		85.01	39.54		4.30	.00	.00
Run	Minutes	192	3.87	10.34		3.88	10.41		0.19	.00	.01
Stair	Minutes	213	10.58	13.06		10.69	15.25		0.53	.17	.27
Cycle	Minutes	115	18.02	30.65		19.27	32.91		0.93	.00	.69
Move	Minutes	213	81.36	35.35		74.69	31.95		3.90	1.00	.00
Other	Minutes	47	1.37	2.07		1.38	2.14		0.07	.22	.29
Stand	Minutes	213	187.57	74.42		195.49	77.59		9.58	.00	.01
Sit	Minutes	213	523.50	139.55		532.52	143.91		26.40	.00	.00
Lie	Minutes	208	93.44	78.76		87.99	82.23		4.54	.61	.00
Sleep	Minutes	213	396.23	87.98		400.52	89.50		19.92	.00	.00
Transitions ⁶	Number	213	1,834.26	638.27		1,788.16	623.33		90.56	.00	.00

Note. Thigh Accelerometry Position Study analyzed with GGIR and ActiPASS software.

¹Relative difference = $(\text{Mean}_{\text{Center}} - \text{Mean}_{\text{Upper}}) / \text{Mean}_{\text{Center}}$. ²Delta is the acceptable deviation. If both $p < .05$, the two means are considered as equivalent. ³Euclidian Norm Minus One (negative values rounded to zero).

⁴Walk slow = Less than 100 steps per minute. ⁵Walk fast = 100 or more steps per minute. ⁶Transition = Change from sit/lie to upright posture.

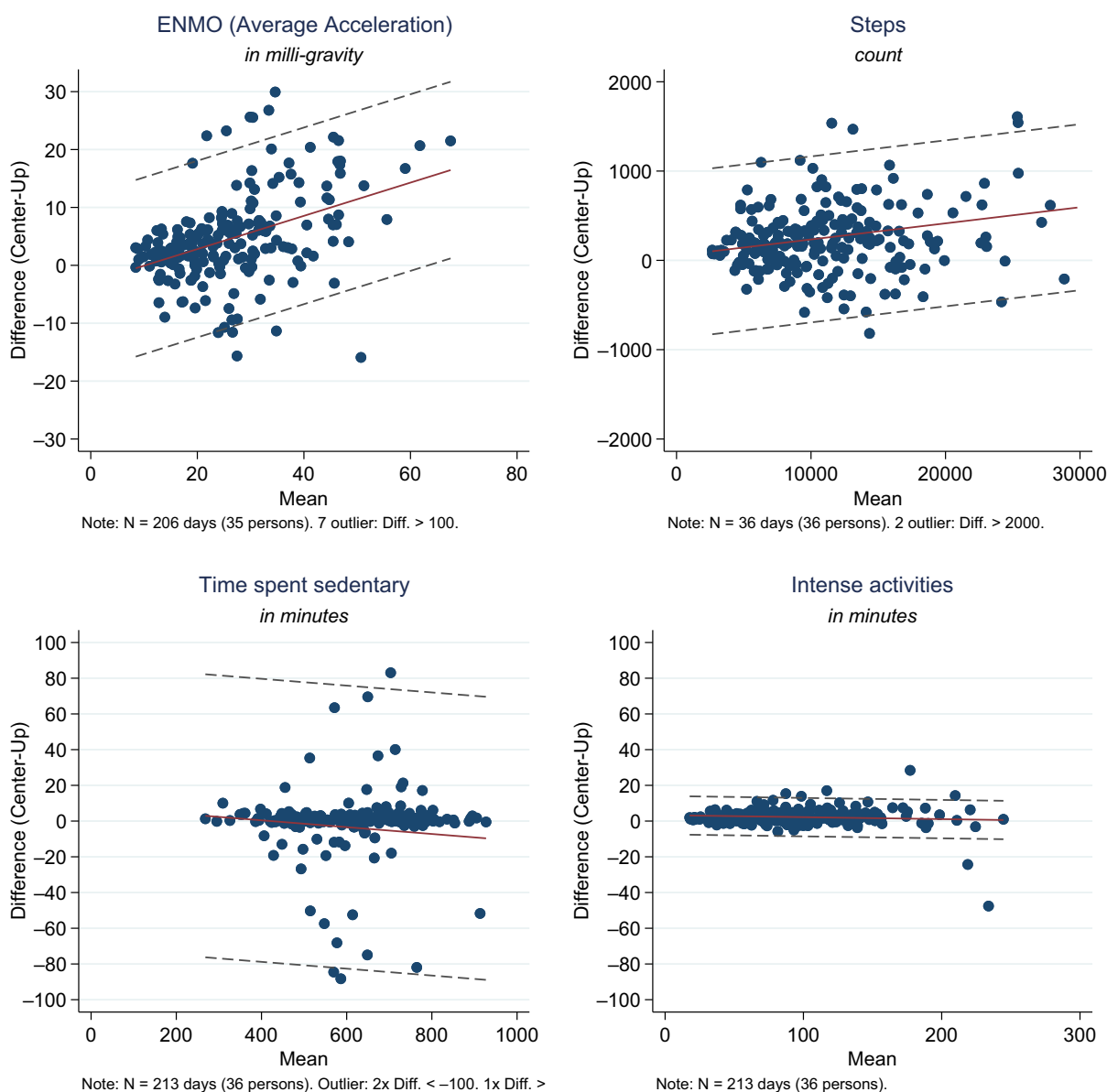


Figure 1 — Bland–Altman plots illustrating the differences in metrics between the center and upper accelerometer placements ($n=36$). Data: Thigh Accelerometry Position Study analyzed with GGIR and ActiPASS. Note: Bland–Altman plots showing the difference in measures between upper and center placement on the y-axis. Positive values indicate a higher metric at upper compared with center-thigh position. The x-axis shows the mean of center- and upper-thigh position. The solid line represents the mean difference, indicated as a trend. The dashed lines indicate the limits of agreement (mean difference \pm 1.96 SDs).

steps per day was 259 ($p = .00$; 95% CI [195.32, 323.09]). For both time per day spent sedentary and Intense Activity, the mean difference between center- and upper-thigh position was less than 4 min, that is, -3.7 ($p = .18$; 95% CI $[-9.13, 1.73]$) and 2.3 ($p = .00$; 95% CI [1.56, 3.04]), respectively.

Most other postures and activities presented in Table 3 (Bland–Altman plots are available in Appendix 1) showed a low mean in the difference of paired measurements, for example, walking time per day differs only by approximately 2 min between the center and upper measurement ($p = .02$; 95% CI [0.32, 3.51]). However, some metrics show (very) high relative LoAR: running (118%), walking stairs (371%), cycling (285%), lying (205%), and “other” movement (924%). A proportional bias was found in slow walking ($\beta = -0.23$; 95% CI $[-0.36, -0.10]$), walking stairs ($\beta = -0.23$; 95% CI $[-0.36, -0.10]$), cycling ($\beta = -0.32$; 95% CI

$[-0.50, -0.14]$), moving ($\beta = 0.47$; 95% CI [0.34, 0.58]), standing ($\beta = -0.35$; 95% CI $[-0.47, -0.22]$), and the number of transitions ($\beta = 0.19$; 95% CI [0.06, 0.33]).

To check whether the distance between the devices was correlated with the difference in the metrics, we performed multivariate regression models, shown in Table 4. The ENMO was influenced by the position of the device: 1 cm higher distance between the center- and upper-thigh position was correlated with almost 1 mg higher difference in ENMO between the two positions ($b = 0.94$; 95% CI [0.26, 1.62]). This translates to 1 cm higher placement (toward the hip) was correlated with 0.94 mg lower average acceleration. For the number of steps ($b = 22.63$; 95% CI $[-26.84, 72.09]$), time spent sedentary ($b = 0.03$; 95% CI $[-2.48, 2.55]$), and Intense Activities ($b = 0.22$; 95% CI $[-0.10, 0.54]$), the position (device gap) had no significant effect on the results of the ActiPASS algorithm.

Table 3 Mean and 95% Limits of Agreement of the Daily Difference Between Center and Upper Placement

Variable	Unit	N	Mean difference ¹	Adjusted 95% limits of agreement		Range from lower limit to upper limit	
				Lower limit	Upper limit	Abs	% to mean
Euclidian Norm Minus One ²	mg	206	4.47***	-10.79	19.73	30.51	109.51
Steps	Number	213	259.21***	-670.24	1,188.66	1,858.90	16.16
Sedentary	Minutes	213	-3.70	-82.94	75.54	158.49	25.78
Intense activities	Minutes	213	2.30***	-8.45	13.05	21.50	23.10
Walk slow ³	Minutes	213	-1.16***	-6.69	4.37	11.06	62.52
Walk fast ⁴	Minutes	213	3.08***	-17.02	23.17	40.19	58.05
Walk	Minutes	213	1.92*	-21.21	25.04	46.25	53.21
Run	Minutes	192	-0.01	-2.06	2.04	4.11	117.60
Stair	Minutes	213	-0.11	-19.74	19.52	39.26	371.09
Cycle	Minutes	115	-1.26	-15.14	12.62	27.76	285.40
Move	Minutes	213	6.67***	-7.79	21.12	28.91	35.54
Other	Minutes	47	-0.01	-1.41	1.38	2.79	923.91
Stand	Minutes	213	-7.92***	-26.06	10.22	36.28	19.34
Sit	Minutes	213	-9.02**	-87.77	69.73	157.50	30.09
Lie	Minutes	208	5.45	-88.04	98.93	186.97	204.91
Sleep	Minutes	213	-4.29	-71.94	63.35	135.29	34.14
Transitions ⁵	Number	213	46.09***	-106.70	198.88	305.58	16.66

Data: Thigh Accelerometry Position Study analyzed with GGIR and ActiPASS. Notes: Bland-Altman plots are available in Figure 1 and Appendix 1. Limits of agreement were adjusted to the nested data structure (multiple observations [days] of same persons).

¹Mean of the (daily) difference between the center- and upper-thigh position. Positive values indicate a higher metric at upper compared to center-thigh position. ²Euclidian Norm Minus One (negative values rounded to zero). ³Walk slow = less than 100 steps per minute. ⁴Walk fast = 100 or more steps per minute. ⁵Transistion = Change from sit/lie to upright posture.

*** $p < .001$. ** $p < .01$. * $p < .05$.

Table 4 Linear Ordinary Least Squares Regression on the Difference (Diff) in the Metrics Derived From Upper- and Center-Thigh Position

	Diff ENMO ²	Diff number of steps	Diff sedentary time	Diff intense activities ³
Number of observations	206	213	213	213
Number of individuals	35	36	36	36
Device gap	0.94**	22.63	0.03	0.22
Mean ¹ Euclidian Norm Minus One	0.28***			
Mean ¹ number of steps		0.02*		
Mean ¹ sedentary			-0.02	
Mean ¹ intense activity ³				-0.01
Height	-0.13	8.61	-0.89	0.03
Thigh length	-0.18	-13.24	2.04	-0.21
Age	0.26**	6.52	-0.44	0.16
Male	5.05	-1.24	4.79	-0.03
Intercept	8.45	-1,231.62	82.26	-0.68
R-squared	.50	.09	.03	.11

Note. Thigh Accelerometry Position Study analyzed with GGIR and ActiPASS.

¹Mean of the two measurements from center- and upper-thigh position. ²Euclidian Norm Minus One (negative values rounded to zero).

*** $p < .001$. ** $p < .01$. * $p < .05$.

The proportional bias, indicated by an increased error with increased ENMO in the Bland-Altman plots, was also confirmed in the regression analysis ($b = 0.28$; 95% CI [0.17, 0.39]) when controlling for additional factors. A significant correlation, that is, bias, appears for the number of steps ($b = 0.02$; 95% CI [0.00, 0.04]), but not for sedentary time

($b = -0.02$; 95% CI [-0.06, 0.02]) and intense activities ($b = -0.01$; 95% CI [-0.05, 0.02]).

The same regression models for all single activities are provided in Appendix 3. Apart from moving ($b = 0.74$; 95% CI [0.20, 1.28]), sitting ($b = -3.09$; 95% CI [-5.87, -0.30]), and lying ($b = 3.13$; 95% CI [0.13, 6.13]), no activity was correlated with the

distance between the devices. Interestingly, the gap between the sensors did have opposing correlations with the detection of sitting and lying which was cancelled out when both activities were combined to sedentary behavior. The position of the accelerometer on the thigh did not significantly influence the results for walking, running, stair walking, cycling, “other,” standing, sleeping, and the number of transitions.

Discussion

In this study, we investigated the difference in the metrics of thigh-worn accelerometers when placed at the center- and the upper-thigh. The results on daily time of physical behaviors when measured with accelerometer placement on center- and upper-thigh position showed that the placement is not crucial for the detection of most postures and activities with ActiPASS, namely sedentary behavior, intense activities, fast walking, walking, running, and sleeping. These activities exhibited no proportional bias in the multivariate regression, no influence of the distance between devices, and equivalent means. Similarly, slow walking, stair climbing, cycling, and “other” activities showed no proportional bias or influence of the distance between devices in the multivariate regression, but they did not have equivalent means. Number of steps, standing time, and transitions were also not influenced by the distance between devices and showed equivalent means; however, these metrics exhibited proportional bias in the multivariate regression. In contrast, an influence of the distance between devices on measurement was observed in ENMO, move, sit, and lie.

Overall, these findings partly support our hypothesis that postures and activities identified by ActiPASS would not differ between the two positions of accelerometers on the thigh. Thus, by using the appropriate metrics, pooling and comparison of thigh-worn accelerometer data can be suitable despite different protocols, that is, deviating placements on the thigh. Specifically, the results show that upper thigh placement is comparable with other accelerometer data collected at the center-thigh by using some of the measures by the ActiPASS software.

However, this does not extend to average acceleration, supporting our hypothesis that the vector magnitude is systematically higher at the mid-thigh compared with the upper thigh position. Our analysis showed that ENMO differed when the accelerometer was placed on the center compared with the upper thigh. A higher placement (toward the hip) was associated with lower acceleration. This result can be explained by the fact that the acceleration of the lower limb is higher close to the knee than close to the hip while moving. As ENMO was influenced by the position on the thigh, it is not a reliable metric for comparisons of differently placed thigh-worn accelerometers. Thus, for accelerometer metrics based on ENMO, such as intensities based on ENMO cut-points, it is recommended to refrain from merging data from different thigh placements. If ENMO or other vector magnitude-based metrics are to be utilized, it may be preferable to position the accelerometer centrally on the body, near the center of mass (e.g., at the hip), or at a well-defined anatomical location such as the wrist. However, this approach was not examined in the present study.

The variation in results for postures and activities detected by ActiPASS across different sensor positions was considerably smaller compared with the substantial variation observed with ENMO (see Table 2). Comparing the means of center- and upper-thigh placement across the whole sample, the relative difference for ENMO was 15.9%, while the difference between the accelerometer placements was only 0.6% and 2.4% for Sedentary

and Intense Activity, respectively. Similar results were found by comparing the 95% limits of agreements. While ENMO had a relative LoAR of 110%, it was only between 16% and 26% for the number of steps, sedentary time, and Intense Activity.

The regression analyses on the (individual) difference between the center- and upper-thigh placement showed that Intense Activity, as well as most postures, and activities were not affected by the position of the sensor on the thigh. Only the detection of moving, sitting, and lying was sensitive to the position of the sensors. Interestingly, sitting and lying were affected by the placement of the devices, but not sedentary time, that is, sitting and lying combined. This finding can be explained by the fact that the algorithm for distinguishing sitting from lying depends on the rotation of the thigh, which seems to be sensitive for placement on the thigh. Misclassification could result from inconsistencies in device placement or the known limitations of using thigh rotation to distinguish between sitting and lying (see [Hettiarachchi et al., 2021](#); [Shivgulam et al., 2023](#)). Importantly, these issues do not impact the overall measurement of sedentary time.

Not all postures and activities were perfectly consistent between the center- and upper-thigh placement, but in general the ActiPASS algorithm provided comparable results, especially when looking at intensity categories, that is, Intense Activity, sedentary behavior, and sleep. This is likely because ActiPASS does not only use the amount of acceleration, but also utilizes the inclination and rotation data features in relation to line of gravity to determine postures and activities. In general, using several acceleration features in combination provided robust estimates that were not as impacted by sensor placement, compared to using only a single acceleration feature (ENMO).

The study population primarily consisted of middle-aged adults (ranging from 26 to 72 years, with a mean age of 39 years). Although older individuals were underrepresented and very old and adolescent participants were not included, there was no reason to assume that the differences between upper-thigh and mid-thigh positions would have varied significantly across other age groups. However, the sample included only healthy, mobile individuals, and the results may have differed in a population with mobility limitations.

Some further shortcomings of the present study must be mentioned. First, we compared accelerometer data from different positions on the thigh without having observations or other measures of the respondents’ “true behaviors.” However, it is worth noting that some TAPS respondents received graphic feedback on their activities, which consisted of a graph illustrating activities over the course of the day, and the majority of respondents evaluated the agreement with their actually performed activities and bedtime as good or very good. Second, the data used did not contain data from lower thigh positions. Accordingly, the conclusions made with the present analysis might not be valid for all possible placements on the thigh.

The question of placement of thigh-worn accelerometer and its consequences for comparability obviously occurs when different placements are instructed in the study protocol. But also, within-study variation can be an issue. When participants are asked to attach the sensor on their own thigh, the same instruction can lead to different interpretations and therefore different positioning of the devices. This is also indicated by distances between the two devices in the TAPS sample that ranged from 2.5 to 13 cm. One reason for these inconsistencies is unclear instructions, for example, “upper thigh” without further specification. Another reason might be that finding the midpoint of the thigh is not obvious, for example, the

midpoint might be estimated differently while standing or sitting. The consistency of the placement is therefore dependent on the quality and intelligibility of the instruction. When participants attach the accelerometers themselves, the variation in the exact position between the participants is expected to be larger compared with studies in which trained interviewers or nurses attach the devices.

After previous studies showed that the results of posture detection from thigh-worn accelerometer are robust for different brands (Crowley et al., 2019; Edwardson et al., 2022), this paper showed that ActiPASS is also quite robust for deviating positions on the thigh. This leads to the promising conclusion that—using the right metrics—data from thigh-worn accelerometry studies with deviating protocols can be pooled, which is further proof of the concept of pooling data promoted by ProPASS.

Acknowledgments

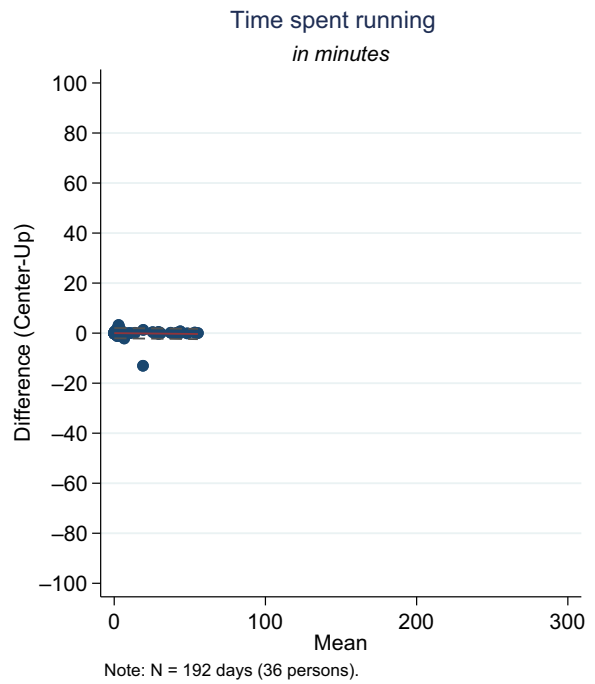
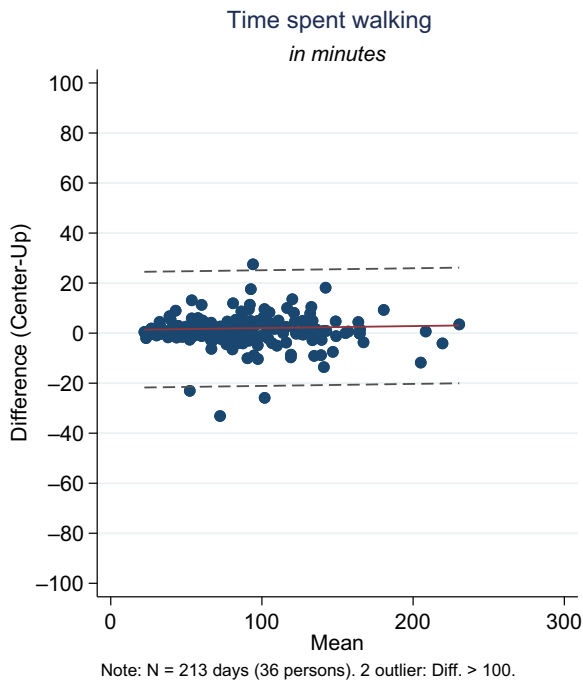
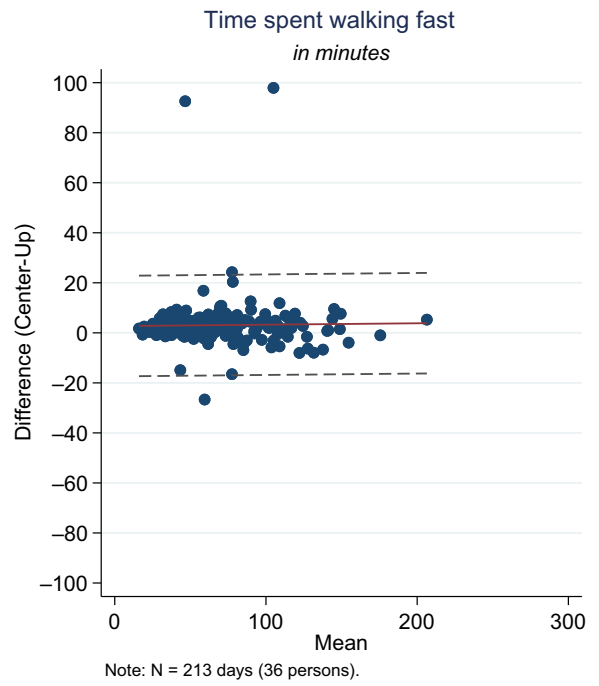
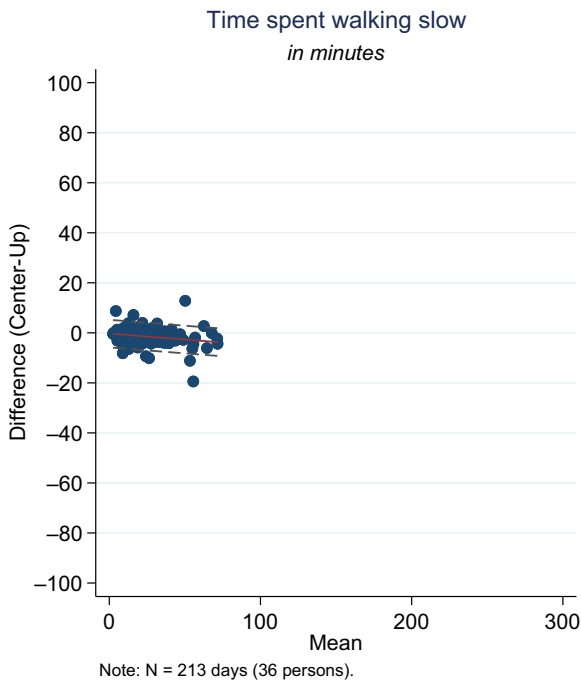
This research was supported by grants from the German Federal Ministry of Education and Research (BMBF) as part of SHARE (grant numbers 01UW1801/01UW2202) for Franzese, The National Heart Foundation (APP 107158) for Ahmadi, and FORTE, Swedish Research Council for Health, Working Life and Welfare (2021-01561) for Johansson and Hettiarachchi.

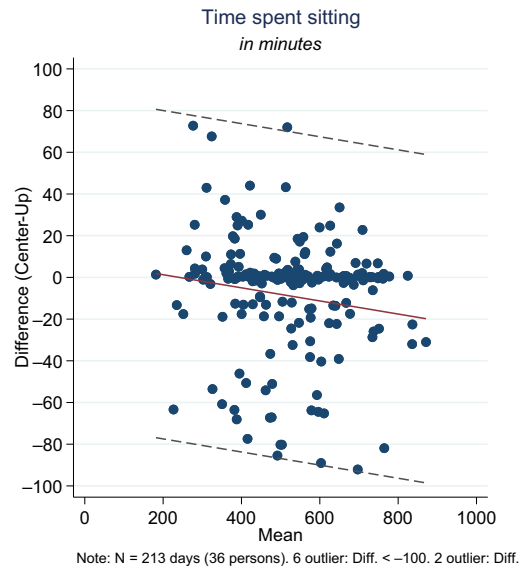
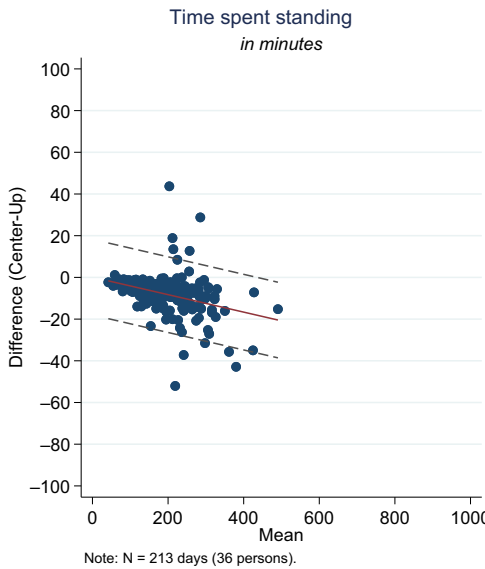
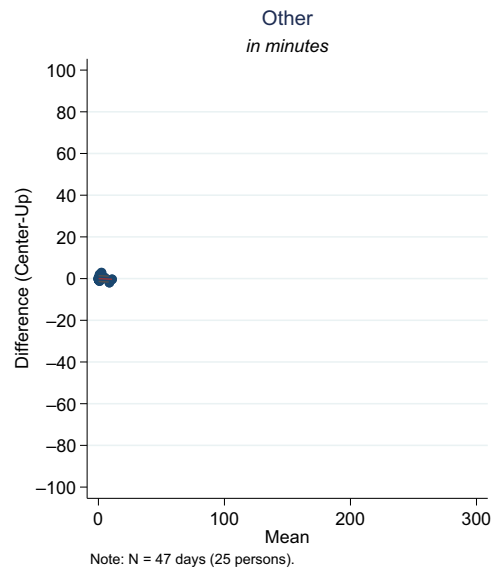
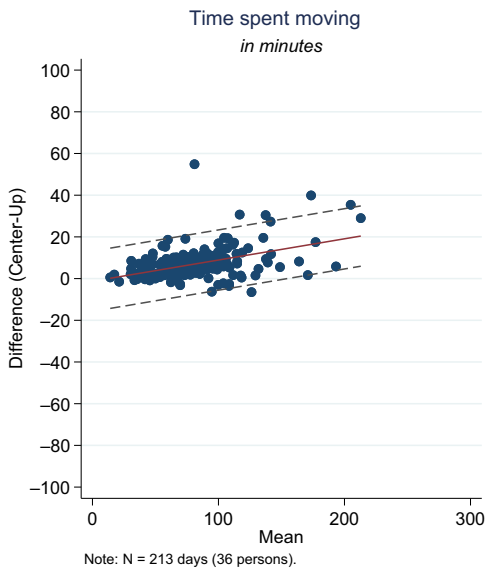
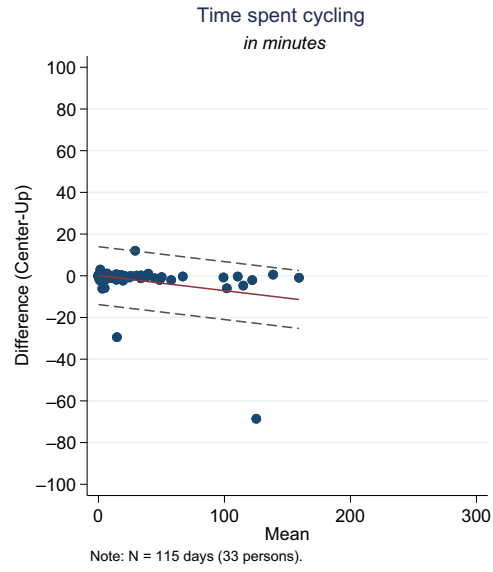
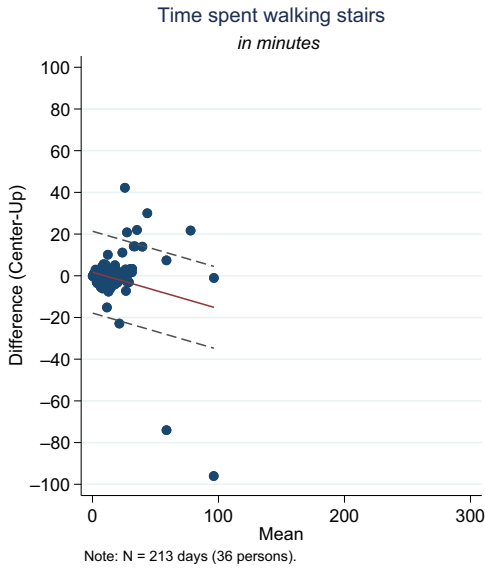
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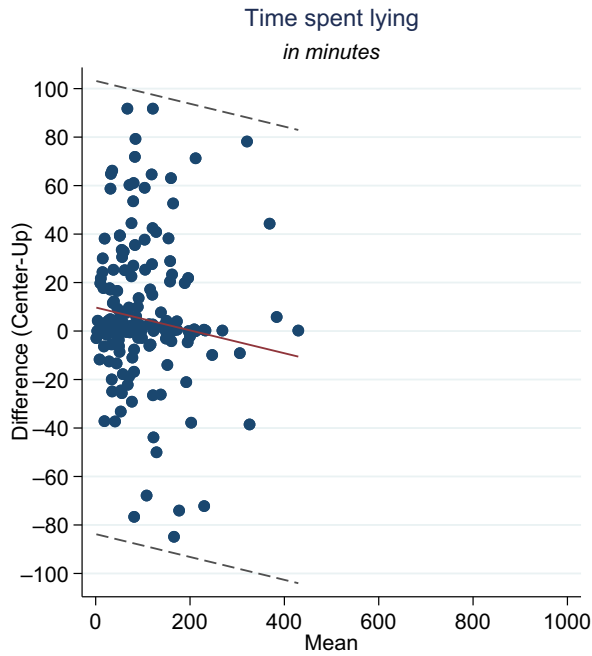
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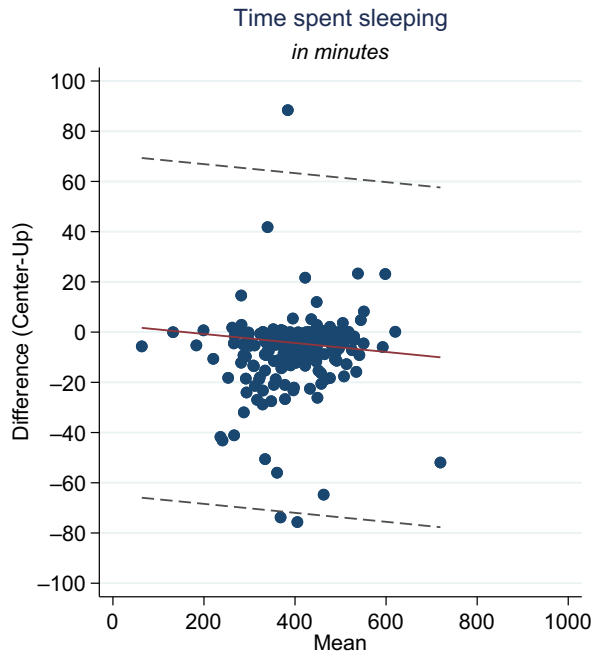
Appendix 1: Bland–Altman Plots



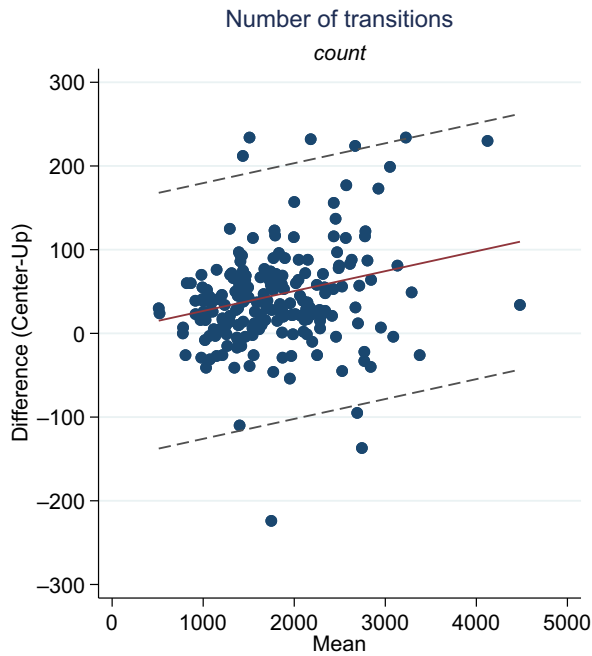




Note: N = 208 days (36 persons). 3 outlier: Diff. < -100. 5 outlier: Diff. > 100.



Note: N = 213 days (36 persons). 2 outlier: Diff. > 100.



Note: N = 36 days (36 persons). 2 outlier: Diff. > 300.

Data: Thigh Accelerometry Position Study analyzed with GGIR and ActiPASS.

Appendix 2: Test for Proportional Bias in Bland–Altman Plots: Linear Ordinary Least Squares Regressions of the Mean on the Difference in the Metrics (Standardized Coefficients and 95% CIs)

Variable	N	Beta	p	CI lower	CI Up
ENMO ¹	206	0.43	.00	0.31	0.56
Steps	213	0.21	.00	0.08	0.34
Sedentary	213	−0.06	.35	−0.20	0.07
Intense activities	213	−0.09	.18	−0.23	0.04
Walk slow ²	213	−0.23	.00	−0.36	−0.10
Walk fast ³	213	0.02	.79	−0.12	0.15
Walk	213	0.03	.70	−0.11	0.16
Run	192	−0.06	.38	−0.21	0.08
Stair	213	−0.23	.00	−0.36	−0.10
Cycle	115	−0.32	.00	−0.50	−0.14
Move	213	0.47	.00	0.34	0.58
Other	47	−0.10	.49	−0.40	0.20
Stand	213	−0.35	.00	−0.47	−0.22
Sit	213	−0.11	.11	−0.24	0.03
Lie	208	−0.08	.27	−0.21	0.06
Sleep	213	−0.05	.51	−0.18	0.09
Transitions ⁴	213	0.19	.01	0.06	0.33

Note. Thigh Accelerometry Position Study analyzed with GGIR and ActiPASS. ENMO=Euclidian Norm Minus One; CI=confidence interval.

¹Euclidian Norm Minus One (negative values rounded to zero). ²Walk slow = less than 100 steps per minute. ³Walk fast = 100 or more steps per minute. ⁴Transistion = Change from sit/lie to upright posture.

Appendix 3: Linear Ordinary Least Squares Regression on the Difference (Diff) in the Metrics From Upper- and Center-Thigh Position

	Diff walk slow	Diff walk fast	Diff walk	Diff run	Diff stair
Number of participants	36	36	36	36	36
Number of observations (days)	213	213	213	192	213
Device gap	-0.04	0.16	0.08	-0.02	0.42
Mean walk slow	-0.04				
Mean walk fast		0.02			
Mean walk			0.02		
Mean run				-0.00	
Mean stair					-0.27
Height	-0.01	0.27*	0.23	0.01	-0.26
Thigh length	-0.00	-0.16	-0.09	0.02*	-0.04
Age	-0.05	-0.08	-0.15	0.00	0.27
Male	0.37	-0.70	-0.05	-0.02	-0.15
Intercept	3.39	-35.95*	-29.04	-3.23*	35.22
R-squared	.09	.05	.05	.03	.19

* $p < .05$. ** $p < .01$. *** $p < .001$.

	Diff cycle	Diff move	Diff other	Diff stand	Diff sit
Number of participants	33	36	25	36	36
Number of observations (days)	115	213	47	213	213
Device gap	-0.11	0.74**	0.06	-0.91	-3.09*
Mean cycle	-0.07				
Mean ¹ move		0.11***			
Mean ¹ other			-0.03		
Mean ¹ stand				-0.03**	
Mean ¹ sit					-0.02
Height	-0.05	0.04	0.02	0.07	-1.07
Thigh length	-0.04	-0.20	-0.07	0.30	1.67
Age	0.01	-0.02	-0.00	-0.14	-0.71
Male	1.17	2.47	-0.31	-4.61	10.13
Intercept	10.60	-4.50	-1.04	-12.47	154.66*
R-squared	.11	.32	.15	.25	.06

* $p < .05$. ** $p < .01$. *** $p < .001$.

	Diff lie	Diff sleep	Diff transitions
Number of participants	36	36	36
Number of observations (days)	208	213	213
Device gap	3.13*	-0.89	2.55
Mean ¹ lie	-0.03		
Mean ¹ sleep		-0.01	
Mean ¹ transitions			0.03**
Height	0.12	0.50	0.80
Thigh length	0.43	-1.67	-1.19
Age	0.29	0.28	-0.82
Male	-4.97	-0.92	27.34
Intercept	-65.22	-11.86	-88.55
R-squared	.03	.03	.12

Note. Thigh Accelerometry Position Study analyzed with GGIR and ActiPASS.

¹Mean of the two measurements from center and upper thigh position.

* $p < .05$. ** $p < .01$. *** $p < .001$.