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RESEARCH

Momentary physical activity, subjective age, and the moderating role of pain

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Abstract

Subjective age, that is felt age compared to chronological age, is an important predictor of health and well-being in later life. It can fluctuate from day to day and from one moment to another. Previous cross-sectional and macro-longitudinal studies have shown that feeling younger is related to physical fitness and exercise. Yet, there is limited knowledge on the effects of physical activity on subjective age in daily life and moderators of this association. We thus aim to investigate the association of momentary physical activity with momentary subjective age, expecting that more activity is related to feeling younger. We further expect that concurrent pain experience attenuates this relationship. $N = 54$ participants aged 50–62 years ($Mage = 56.1$ years, 75% female) wore chest-sensors measuring their physical activity (step count, movement acceleration) for one week and reported on their subjective age five times per day. Multilevel regression analyses revealed between and within-person variation in momentary subjective age (ICC = 0.74), pain (ICC = 0.63) and physical activity (ICC Moac30 = 0.078, steps30 = 0.053). Pain emerged as a consistent predictor of momentary subjective age ($b = 4.64$, $p = 0.000$), whereas results were mixed for the physical activity measures. No significant moderating effect of pain was observed on the relationship between physical activity and subjective age. Our study shows the importance of pain experiences for momentary subjective age, whereas the role of momentary physical activity needs further exploration.

Keywords Subjective age · Pain · Physical activity · Midlife · Ambulatory assessment

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An increasing number of people is living to very advanced ages, and consequently, we need to understand and promote how people can age well. Subjective age, i.e., the age people feel compared to their chronological age, is an important variable in this regard, being both predictive of developmental outcomes, and reflecting several biopsychosocial aging processes (Kotter-Gruhn et al. 2015; Montepare 2009; Weiss & Weiss 2019). Long-term and experimental dynamics of subjective age have been well studied, but less is known about the dynamics of subjective age in participants' daily life. Subjective age is associated with physical activity, which is considered important for healthy aging (e.g., (Baker et al. 2009)). Engaging in less physical activity is for example associated with feeling older over time (Stephan et al. 2020a, b). The relation between physical activity and subjective age might, however, be dependent on other factors, such as the experience of pain. More pain tends to increase the age people feel (Barrett & Gumber 2020; Wettstein et al. 2024) and to impact daily variations in subjective age (Kotter-Grühn et al. 2015). In the current study, we thus investigate how objective and subjective measures of physical activity are associated with the subjective aging experience of middle-aged adults, and whether the experience of pain affects this relationship.

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Subjective age and physical activity in later life

Subjective age has become an important factor in aging research and in the study of "successful aging" (Sabatini et al. 2024). Starting in their late twenties, most people feel younger than their chronological age, and this experience persists up to advanced ages (Pinquart & Wahl 2021). A younger subjective age has been longitudinally and cross-sectionally related to a diverse set of positive health outcomes in later life such as better physical and psychological health (Alonso Debreczeni & Bailey 2020; Westerhof et al. 2023). Physical activity is one important mediator of this relationship, as participants who feel older also report being more inactive (Stephan et al. 2018).

In addition to being a predictor of developmental outcomes, however, subjective age is also conceptualized as a biopsychosocial marker of aging, as the age people feel is assumed to reflect their overall health, well-being, and functioning (Kotter-Gruhn et al. 2015; Stephan et al. 2015). Thus, the relationship of subjective age with many indicators of health and well-being, such as physical activity, is likely reciprocal: Bodily sensations, and physical functioning influence people's felt age (e.g., Barrett and Gumber 2020). People experiencing health through physical activity likely feel more positive about their aging process and therefore feel younger (Stephan et al. 2020a, b). Social comparison processes might also play a role as people who consider themselves as more active and physically stronger than their peers are likely to feel younger (Hughes & Lachman 2016; Stephan et al. 2013).

Several studies have provided evidence for the association of physical activity and subjective age (e.g., Alonso Debreczeni & Bailey 2020; Chen et al. 2018; Heimrich et al. 2022; Stephan et al. 2020a, b; Wang et al. 2022). For instance, in a cross-sectional study, Heimrich et al. (2022) found that engaging in sports more frequently was related to feeling younger in a representative German sample. Longitudinally, Stephan et al. (2020a, b) found that engaging in more physical activity predicted feeling younger 8–20 years later.

In sum, there are theoretical and empirical arguments for a reciprocal association between subjective age and physical activity, and specifically an effect of physical activity on felt age. However, evidence is limited in terms of short-term variations in subjective age, as few studies so far have investigated this relationship in real-life settings.

Subjective age and physical activity in daily life

In everyday life, adults come across situations that make their age more salient. The course of a day holds a wide range of changing situations, sensitivities, and personal interpretations, and a person can go from a moment of feeling old to one of feeling younger. This is framed in the contextual model of Hughes and Touron (2021) which describes subjective age within people's momentary context. Thus, increasing the focus on the daily life context is important for understanding the dynamics underlying the construction of subjective age.

Indeed, subjective age varies in daily and momentary time frames. Kotter-Grühn et al. (2015), for instance, found considerable within-person variability of subjective age in a daily-diary study and demonstrated that intra-individual increases in subjective age were predicted by health problems, stress, and negative affect. On a more fine-grained timeline, Kornadt et al. (2021) found that 25% of the variability in momentary subjective age could be attributed to within-person variation, with an average variation of 3 years from one measurement occasion to the next. Again, there are both theoretical arguments and empirical studies indicating that subjective age shows meaningful short-term fluctuations Understanding these fluctuations gives insight into the process shaping subjective aging experiences in daily life and contributes to a better understanding of their translation into long-term developmental outcomes (Hughes & Touron 2021).

Relatedly, exploring physical activity in daily life is crucial for understanding its intrapersonal dynamics and associations to various (age-related) outcomes (Reichert et al. 2020). Notthoff et al. (2018), for instance, compared the relationship of subjective age and walking speed (as an indicator of physical functioning) in the laboratory and in real life and found that people who felt younger did indeed walk faster. This was however only the case in the laboratory and not in real life. Thus, the effects of physical activity on people's subjective age seem to depend on how and where it is measured.

Furthermore, people rely on heuristics when reporting on past events, and these reports are, consequently, usually biased (Burchartz et al. 2020; Gilovich et al. 2002). In particular, physical activity measures are often influenced by social desirability (Brenner & DeLamater 2014). Leveraging objectively measured physiological data provides an ecologically valid measure of within-person processes over time (Reichert et al. 2020). Additionally, subjective and objective measures of physical activity have been estimated to only covary about 16 percent (Adamo et al. 2009), indicating that subjective and objective measures can provide different information about individual processes.

Taken together, assessing both subjective age and physical activity in daily life provides us with ecologically valid data from people's daily experiences and allows us to investigate the association of both variables on intra- and interpersonal levels. Recently, Schmidt et al. (2024) demonstrated that taking more daily steps was associated with younger subjective ages in a sample of older adults who reported on their subjective age and wore a sensor measuring their physical activity. However, they assessed subjective age only on a daily level, and did not investigate further moderating effects.

Subjective age and physical activity—the role of pain

Both physical activity and subjective age are anchored in bodily experiences. These internal experiences could thus influence their association by providing a shared context. This idea is also represented in the theoretical framework by Hughes and Touron (2021), stating that the internal condition of the individual likely affects their felt age. Pain represents such a bodily condition and is indeed associated with both physical activity and subjective age (Kotter-Grühn et al. 2015; Naugle & Riley 2014).

Some studies have shown association between physical activity and pain. Different levels of pain are related to lower probability of engaging in physical exercise (Axon & Maldonado 2023). An ambulatory assessment study on the momentary association between physical activity and pain found that when participants took more steps than usual before the prompt, they were more likely to experience pain at the prompt (Davis et al. 2023). Moreover, physical activity can also have negative associations with pain as moderate to vigorous activity can reduce the symptoms from chronic pain (Naugle & Riley 2014). A recent review on ambulatory assessment studies examining the association between physical activity and pain showed that the association is complex as results across studies are highly heterogeneous (Tynan et al. 2024). Thus, the association of physical activity and pain needs further exploration.

Empirical findings also relate pain to subjective age. Kotter-Grühn et al. (2015) found that pain contributed to the prediction of daily within-person variation in subjective age in a daily context; the more pain participants experienced, the higher their subjective age. Additionally, Barrett and Gumber (2020) found that everyday body problems such as pain affect people's age identity, making them feel older. Likewise, associated with relatively older subjective ages (Booker et al. 2020). Longitudinally, more pain has been associated with older felt age on both between- and within-person levels (Wettstein et al. 2024). Altogether, this shows a possible direct effect of pain on subjective age.

Besides, by providing a specific context pain likely moderates the effect of physical activity on subjective age. It is plausible that for adults in late middle age, being more physically active is associated with feeling younger, but this may be contingent on concurrent pain experience. First, increased pain during exercise may remind adults that they are getting older (Karp 1988). This is especially relevant in late middle age, which is characterized by a higher frequency of major bodily events like menopause (Talaulikar 2022), onset of illnesses like strokes (Seshadri et al. 2006) or cancers (Yancik 2005), and a decrease in muscle mass (Yancik 2005). Second, increased pain sensations during physical activity may activate comparisons to younger ages when physical activity was not associated with pain, and thus, increase felt age. Finally, more pain experiences during exercise might activate such old age stereotype that pain is a normal part of physical activity, and thus increase subjective age.

In sum, physical activity and subjective age are both associated with the experience of pain. However, we do not know much about the momentary relationship between these variables. There are theoretical foundations in place that offer possible frameworks for how pain can play a role in the subjective aging experience, yet there are few studies exploring their associations.

Aims and hypotheses

The current study aims to explore how momentary subjective age is associated with objectively measured physical activity in a daily context. We expect people's physical activity to be associated with how old they feel: if people are more active at a given moment, the younger they feel consecutively. We expect that if people experience more pain than usual, the relationship between physical activity and subjective age is reversed, i.e., more physical activity with a higher concurrent pain experience should increase subjective age.

Method

Sample

Data collection took place from June to December 2021. The sample consisted of $N = 54$ participants aged 50–62 ($Mage = 56$, $SD = 3.88$), where 74% were female, 24% male, and one participant reported their gender as "other." Participants were recruited through online and paper distribution of flyers in social media, local senior centers, hairdressers, and cafés. The flyer advertised the study as focusing on participants' experience of aging and explicitly mentioned that physical activity would be measured. Participation requirements were age 50–65 and reading capacity in French or German. Exclusion criteria were physical walking disabilities or known heart conditions (to ensure validity of the sensor measurement). Sample size selection followed recommendations of Arend and Schäfer (2019) to have a sample size of 50 at level-1 for detecting medium-sized effects. A total of 52 people were included in the final multilevel analysis as two participants were missing sensor data and were therefore excluded.

Procedure

All participants came to an initial laboratory assessment where they signed consent forms, completed baseline questionnaires, and were fitted with the ECG-sensor for physiological measurements. They were informed that the sensor would measure their heart rate, activity, and body temperature throughout the study. Participants received information on usage of the sensor and were guided to install and use a mobile application for the ecological momentary assessment (EMA) sampling scheme (see below). A demonstration of the application scheme was performed. For participants whose phones did not match the requirements for the app, or those who did not want to use their own phones, we provided a tablet for the duration of the study (Lenovo M7). On the 7 days following the baseline assessment, participants received five EMA prompts per day at 09, 12, 15, 18 and 21 o'clock, respectively. After this week, participants returned with the sensor and tablet and answered a short questionnaire about their experience of participating in the study. Participants received three multipurpose vouchers with a combined value of 90 euros (two vouchers at initial session and one at final session) for their participation as well as personalized feedback on their personality and physical activity, which was sent to them after data were processed. The study was approved by the Ethics Review Panel of the University of Luxemburg (*ERP 21-016 SADIE)*.

Measures

Data were collected in three ways: a baseline assessment consisting of paper–pencil questionnaires focusing on general information and trait measures of subjective age and physical activity, an EMA displayed on participants' phone/tablet, focusing on momentary subjective experiences (subjective age and pain), and a continuous measure of physiological activity measured by a chest-worn sensor. Metabolic equivalent of task (MET), body mass index (BMI), and sociodemographic information were assessed at baseline and used as control variables. 46.3% of participants answered the questions in French and 53.7% in German.

Baseline questionnaire

Metabolic equivalent of task—MET Participants' self-reported overall activity level was assessed at baseline with the International Physical Activity Questionnaire—short form (IPAQ-SF, (Craig et al. 2003)). Participants reported how many minutes of moderate and vigorous activity, walking and sitting they engaged in over the past 7 days. The reported minutes on the different activity intensities were used to calculate the overall metabolic equivalent of task (MET) scores according to the IPAQ scoring manual. One MET represents the energy spent while being sedentary, moderate activity includes a range of 3–6 MET's, while 6 METs and above are categorized as vigorous activity. For this study, the average MET scores for the last 7 days were used in the analyses. MET scores were Box Cox transformed, to correct for skewed data (Malik et al. 2018).

BMI Participants reported their height and weight which were used to calculate participants' BMI scores, which were then Box Cox transformed.

Ecological momentary assessment

Questionnaires on tablets/smartphones were presented through the MovisensXS Platform (version 1.5) and the app installed on the tablets (Movisens, GmbH, Karlsruhe, Germany). Participants were invited to answer questions at five fixed timeslots per day. Momentary subjective age and pain experiences were assessed as well as indicators of well-being, affect, activity, and social interaction (which are not relevant for the present study).

State subjective age Momentary felt age was measured asking participants "Many people feel younger or older than they actually are. This feeling younger or older can fluctuate from day to day or even within a day. Apart from your actual age, how old do you feel at the moment? (Age in years)." Participants manually inserted a number indicating how old they felt in the given moment. Subjective age was calculated by subtracting this number from participants' chronological age, so that a negative number would indicate feeling younger. Scores three standard deviations above and below the mean of the overall sample were removed (more than -29.48 years younger or more than 15.28 years older, this included 2.2% of scores).

Pain The subjective momentary experience of pain was assessed by asking people "How much pain or physical discomfort do you experience right now?". Participants reported their pain experience on a sliding scale ranging from very bad to very good providing a variable ranging from 0 to 100. Pain was Box Cox transformed.

Sensor data

Participants were invited to wear sensors measuring physiological data during the week of the study. The physiological data were recorded with Movisens ECG4Move sensor (Movisens GmbH, Karlsruhe, Germany). The output rate of the sensor is 64 Hz/s, and it has a measurement range of + -16 g (gravity units). The sensor was chest-worn with a belt. Participants were instructed to always wear the sensor except during showers. Data were processed with the Movisens Analyzer software offering output of different physiological indicators with 60 s intervals. For the current study, we used movement acceleration and step count as measures of physical activity. The data of interest were imported into SPSS 29, and intervals of 10, 20 and 30 min before participants finished the next EMA-questionnaire were extracted for step count and movement acceleration. As there is little research and no consistent recommendation to choose the time intervals, we refer to acute exercise which is defined as bouts of exercise with a duration of 1–60 min (Basso & Suzuki 2017) and investigated these three different time frames separately to increase the robustness of our findings.

Movement acceleration Movement acceleration measures the person's physical activity by detecting movement intensity and direction. The movement acceleration variable refers to each person's average score (Moac10, Moac20, Moac30, respectively). A higher score indicates that a person has had higher intensity in their movement during the measured time interval. Data for each time interval were checked for outliers (by a visual examination of the data distribution), and correlational analysis was conducted with and without the most extreme cases, which revealed no significant impact of the outliers, and all scores were kept for further analysis. Furthermore, a Box Cox transformation (Malik et al. 2018) was performed due to an initial positive skew of the distribution (resulting in a normal distribution).

Step count Step count refers to the number of steps a person is walking in the given interval. Step count was computed summing up the number of steps for the given time interval (Steps10, Steps20, Steps30), and checked for extreme cases (by a visual examination of plots). Removing these extreme values, however, greatly reduced the *N* of analyses ($N = 1508$). Thus, multiple transformations were tested and a log10 + 10 transformation provided the best distribution, adjusted for a positive skew of the scores and reduced the impact of the most extreme scores. It was therefore performed on all three time intervals ($N = 1851$).

Analyses

As a first step, descriptive statistics and bivariate correlations were computed with SPSS 29, investigating means and bivariate relationships between variables. To test for variance attributable to between- and within-person differences, we computed intraclass correlations (ICCs). The higher the ICC, the more variance is associated with the between-person level (Rönkkö 2020).

To investigate our main research questions, we ran multilevel regression models with Mplus 8 (Muthén and Muthén, 1998–2023), predicting momentary subjective age by the respective predictor variables. We ran models separately for each of the six physical activity variables. Each model included one of the six physical activity variables. All variables used on the within-person level only were group-mean centered, all variables used on the between-person level only were grand mean centered (Enders & Tofighi 2007). For variables used at both levels, variables were not centered a priori, as in this case, Mplus automatically applies latent group-mean centering (Asparouhov & Muthén, 2019).

We first computed models containing only the within-person level (L1), and predictor variables (group-mean centered) were entered stepwise: (1) physical activity (movement acceleration or step count), (2) physical activity and pain, (3) physical activity, pain, and the moderation term. In a second step, both the within-person (L1) and between-person (L2) levels were included in the analysis. Again, predictors were included stepwise: (1) physical activity on both levels, and pain on both levels, (2) physical activity, pain, and the moderation term, all on both levels, (3) physical activity, pain, and the moderation term on both levels, including the between-person covariates BMI, MET, and age on level 2 (grand mean centered). The equations for the final models are as follows:

Level 1 Model:

$$\text{SSA}_{ij} = \beta_{0j} + \beta_{1j} \cdot \text{Physical Activity}_{ij} + \beta_{2j} \cdot \text{Pain}_{ij} + \beta_{3j} \cdot \text{Moderation}_{ij} + e_{ij}$$

Level 2 Model:

$$\beta_{0j} = \gamma_{00} + \gamma_{01} \cdot \text{Physical Activity}_j + \gamma_{02} \cdot \text{Pain}_j + \gamma_{03} \cdot \text{Moderation}_j + \gamma_{04} \cdot \text{Age}_j + \gamma_{05} \cdot \text{BMI}_j + \gamma_{06} \cdot \text{MET}_j + u_{0j}$$

$$\beta_{1j} = \gamma_{10} + \gamma_{11} \cdot \text{Physical Activity}_j + \gamma_{12} \cdot \text{Pain}_j + \gamma_{13} \cdot \text{Moderation}_j + \gamma_{14} \cdot \text{Age}_j + \gamma_{15} \cdot \text{BMI}_j + \gamma_{16} \cdot \text{MET}_j + u_{1j}$$

$$\beta_{2j} = \gamma_{20} + \gamma_{21} \cdot \text{Physical Activity}_j + \gamma_{22} \cdot \text{Pain}_j + \gamma_{23} \cdot \text{Moderation}_j + \gamma_{24} \cdot \text{Age}_j + \gamma_{25} \cdot \text{BMI}_j + \gamma_{26} \cdot \text{MET}_j + u_{2j}$$

$$\beta_{3j} = \gamma_{30} + \gamma_{31} \cdot \text{Physical Activity}_j + \gamma_{32} \cdot \text{Pain}_j + \gamma_{33} \cdot \text{Moderation}_j + \gamma_{34} \cdot \text{Age}_j + \gamma_{35} \cdot \text{BMI}_j + \gamma_{36} \cdot \text{MET}_j + u_{3j}$$

Results

Preliminary and descriptive statistics

An overview of descriptive statistics, bivariate correlations, and ICCs is displayed in Table 1. In terms of associations between variables, between-person correlations revealed that momentary subjective age and all three movement acceleration measures were significantly correlated: Moac10 at $r = -0.13$ ($p < 0.001$), Moac20 at $r = -0.14$ ($p < 0.001$), and Moac30 at $r = -0.11$ ($p = 0.001$). Momentary subjective age was further unrelated to step count measures of 10 and 20 min: Steps10 $r = -0.00$ ($p = 0.896$), Steps20 $r = -0.01$ ($p = 0.564$), but did significantly relate to step count of 30 min: Steps30, $r = -0.04$ ($p = 0.035$). Momentary subjective age was significantly correlated with pain ($r = -0.57$, $p < 0.001$), and it was also correlated with baseline activity levels: MET, $r = -0.37$ ($p < 0.001$). Pain was negatively correlated with all physical activity measures.

In line with previous work (Kornadt et al. 2021), 25% of the variability in momentary subjective age could be attributed to within-person variation (ICC = 0.74). Nine participants had zero variation in their momentary subjective age, meaning that they reported the same age at every measurement. For all time intervals, variability in movement acceleration was mostly within-person (ICCs = 0.07 – 0.08, Table 1), indicating that the variance does not change drastically depending on the time scale used. This was similar for the three step count measures with ICCs of 0.05 for all time intervals (Table 1). Finally, the ICC for pain was 0.63 which means that around 40% of the variation in pain could be explained on the within-person level.

Momentary physical activity and momentary subjective age

As a first step, momentary physical activity measures were entered as predictors of momentary subjective age. For all three time intervals, movement acceleration significantly predicted momentary subjective age (Table 2, Model 1, see Appendix Tables 4 and 5 for the 20- and 30-min intervals). People who moved more than usual in the given timeframe reported feeling younger at the following prompt compared to. This effect did not hold when pain was included in the models (Table 2, Model 2). None of the step count measures reached significance (Table 3, Model 1, see Appendix Tables 6 and 7 for 20- and 30-min intervals). These findings partly support our hypothesis: If people are more active in a given moment, they feel younger subsequently.

In the second step, we created two-level models with between-person predictors. Pain remained a significant predictor of momentary subjective age on the within-person level, while physical activity measures remained non-significant in the two-level models (Table 2, Model 4, see Appendix Tables 4, 5, 6 and 7—for 20- and 30-min intervals, respectively). The final models, including covariates, showed that MET was negatively associated with momentary subjective age, indicating that people who in general report being more active also report feeling younger. BMI was positively related to subjective age, indicating that the higher the BMI, the older people feel. Age was negatively related to momentary subjective age, indicating that the higher the chronological age, the younger people feel.

The moderating role of momentary pain

To test the hypothesis that the experience of pain moderates the relationship between physical activity and subjective age, the interaction term for pain and physical activity was entered into the models (Tables 2 and 3, and Appendix Tables 4, 5, 6, and 7, models 3, 5 and 6, respectively). Movement acceleration became non-significant when including pain in the models whereas pain was a consistent predictor of subjective age in all models: In moments when participants experienced more pain than usual, they felt older. The moderating effect of pain on the relationship between physical activity and subjective age was not significant in any of the models. The effect of pain on momentary subjective age on level-1 remained significant also in the two-level models and when covariates were included (Tables 2 and 3, and Appendix Tables 4, 5, 6 and 7, models 4, 6 and 7).

Discussion

In the current study we investigated the association of subjective age and physical activity in participants' daily life, and whether the experience of pain could alter this relationship. By combining ambulatory assessments and physiological sensor measures, we included both subjective and objective indicators of people's daily life experiences and the investigation of inter- and intrapersonal variation. We built on previous work relating subjective age and physical activity (Heimrich et al. 2022; Schmidt et al. 2024; Stephan et al. 2020a, b) and demonstrated a possible short-term relation between movement acceleration and momentary subjective age. No significant association was found between step count and momentary subjective age. Furthermore, pain did not moderate the association of physical activity and momentary subjective age but emerged as a significant predictor of momentary subjective age across all within-person models, even when

Table 1 Descriptive statistics and bivariate correlations for all study variables. Between-person pearsoncorrelations are displayed below the diagonal

Variable	*n*	*M (SD)*	*ICC*	1	2	3	4	5	6	7	8	9	10	11
1 SSA	2343 (54)	−6.90 (6.60)	0.741	–										
2 Moac10	2256 (52)	0.50 (0.29)	0.072	−0.13*	–									
3 Moac20	2256 (52)	0.50 (0.29)	0.078	−0.14*	0.98*	–								
4 Moac30	2256 (52)	0.50 (0.29)	0.078	−0.11*	0.95*	0.98*	–							
5 Steps10	2256 (52)	1.56 (0.56)	0.046	−0.0	0.84*	0.82*	0.77*	–						
6 Steps20	2256 (52)	1.80 (0.64)	0.052	−0.01	0.86*	0.88*	0.84*	0.96*	–					
7 Steps30	2302 (52)	1.98 (0.66)	0.053	−0.04*	0.84*	0.87*	0.88*	0.89*	0.95*	–				
8 Pain	2343 (54)	0.50 (0.28)	0.631	0.57*	−0.25*	−0.28*	−0.33*	−0.13*	−0.15*	−0.19*	–			
9 MET	1936 (45)	0.50 (0.29)		−0.37*	0.18*	0.23*	0.23*	0.18*	0.23*	0.22*	−0.30*	–		
10 AGE	2343 (54)	56.02 (3.88)		−0.29*	−0.01	−0.01	−0.04	−0.07*	−0.06*	−0.08*	−0.05*	0.06*	–	
11 BMI	2343 (54)	0.50 (0.29)		0.36*	−0.18*	−0.18*	−0.20*	−0.17*	−0.18*	−0.18*	0.30*	−0.26*	−0.08*	–

SSA, State subjective age; Moac10, Movement acceleration 10 min; Moac20, Movement acceleration 20 min, Moac30, Movement acceleration 30 min; Steps10, Step count 10 min; Steps20, Step count 20 min; Steps30, Step count 30 min, Pain, Momentary pain; MET, Metabolic equivalent of task; BMI, Body mass index. N refers to the within-level units of analyses, the N in brackets to the between-level units of analyses

*$p < 0.05$

Table 2 Multilevel regression analyses predicting momentary subjective age from movement acceleration (10-min interval), pain, interaction term, and covariates

Variable	Model 1		Model 2		Model 3		Model 4		Model 5		Model 6	
	b(SE)	*p*	*b*(SE)	*p*	*b*(SE)	*p*	*b*(SE)	*p*	*b*(SE)	*p*	*b*(SE)	*p*
Within												
Moac10	**−0.90 (0.40)**	**0.026**	−0.75 (0.41)	0.071	−0. 0.74 (0.42)	0.078	−0.75 (0.41)	0.070	0.15 (2.41)	0.949	0.24 (2.37)	0.918
Pain			**4.62 (1.03)**	< 0.001	**4.63 (1.04)**	< 0.001	**4.62 (1.03)**	< 0.001	**5.38 (2.42)**	0.026	**5.45 (2.38)**	0.022
Moderation					−1.30 (3.69)	0.725			−1.68 (4.30)	0.696	−1.83 (4.21)	0.662
Between												
Moac10							−1.03 (9.31)	0.912	13.48 (16.43)	0.412	28.48 (26.978)	0.291
Pain							**14.78 (3.81)**	< 0.001	**25.98 (11.02)**	0.018	30.01 (36.26)	0.130
Moderation									−25.63 (22.67)	0.258	−41.50 (41.87)	0.322
BMI											3.72 (2.29)	0.105
MET											**−5.12 (1.98)**	0.009
Age											**−0.314 (0.14)**	0.020
R2within	0.005	0.241	0.054	0.001	0.054	0.002	0.055	0.001	0.076	0.412	0.079	0.413
R2between							0.318	0.001	0.664	0.005	0.847	< 0.001

b = unstandardized regression coefficient. SE = standard error. Values significant at $p < 0.05$ are in bold. Model 1: within-level only with movement acceleration. Model 2: within-level only with movement acceleration and pain. Model 3: within-level only with movement acceleration, pain and moderation. Model 4: two-level model with movement acceleration and pain, Model 5: two-level model with movement acceleration, pain and moderation. Model 6: two-level model with movement acceleration, pain, moderation, and covariates

Table 3 Multilevel regression analysis predicting momentary subjective age with step count (10-min interval), pain, the interaction term, and covariates

Variable	Model 1		Model 2		Model 3		Model 4		Model 5		Model 6	
	b(SE)	*p*	*b*(SE)	*p*	*b*(SE)	*p*	*b*(SE)	*p*	*b*(SE)	*p*	*b*(SE)	*p*
Within												
Steps10	−0.22 (0.17)	0.184	−0.17 (0.18)	0.325	−0.17 (0.18)	0.326	0.17 (0.18)	0.327	0.31 (0.98)	0.748	0.33 (0.97)	0.733
Pain			**4.65 (1.03)**	< 0.001	**4.65 (1.02)**	< 0.001	**4.65 (1.03)**	< 0.001	**5.94 (2.96)**	0.044	**5.98 (2.93)**	0.041
Moderation					0.55 (1.62)	0.737			−0.96 (1.83)	0.601	−0.98 (1.81)	0.587
Between												
Steps10							3.00 (7.09)	0.673	7.38 (8.13)	0.364	13.50 (8.60)	0.117
Pain							**15.02 (3.72)**	< 0.001	**23.54 (7.18)**	0.001	25.29 (10.68)	0.018
Moderation									−6.01 (4.44)	0.176	−9.64 (7.17)	0.179
BMI											4.08 (2.59)	0.114
MET											**−5.06 (2.07)**	0.015
Age											**−0.30 (0.13)**	0.027
R2within	0.001	0.499	0.052	0.004	0.052	0.004	0.053	0.004	0.096	0.445	0.098	0.439
R2between							0.329	0.001	0.596	0.000	0.767	< 0.001

b = unstandardized regression coefficient. SE = standard error. Values significant at $p < 0.05$ are in bold. Model 1: within-level only with step count. Model 2: within-level only with step count and pain. Model 3: within-level only with step count, pain and moderation. Model 4: two-level model with step count and pain. Model 5: two-level model with step count, pain, and moderation Model 6: two-level model with step count, pain, moderation, and covariates controlling for between-person variability: in moments of more pain than usual people tend to feel older.

The association of physical activity and subjective age

In our study, movement acceleration was negatively related to momentary subjective age, indicating that more movement than usual goes along with a younger subjective age which is in line with previous findings (Heimrich et al. 2022; Stephan et al. 2020a, b). Findings were weaker for step count, which showed a small, between-level, bivariate relation to subjective age in the larger time interval. In the initial within-level regression analysis, movement acceleration predicted momentary subjective age, whereas step count did not. This is in contrast to previous findings by Schmidt et al. (2024), who found significant associations between activity measures and subjective age, albeit on the daily and not momentary level and in a sample with a broader age range.

Including the two activity measures allows for a broader comparison across diverse methodologies in the field (Burchartz et al. 2020). Our results show that the means of measurement as well as the timeline of assessment may be crucial for discovering important relations. Although both variables are indicators of physical activity, they differ in qualitative aspects. Step count provides an apprehensible concept of physical activity but informs less about underlying efforts. Movement acceleration represents activity intensity: The quicker ones' movements, the higher the intensity. Steps and movement acceleration could thus represent physical activity performed for different purposes: Higher movement acceleration likely represents structured exercise, more steps likely a broader range of daily life activities. Taken into consideration, a certain intensity might be needed for physical activity to impact felt age.

The initial positive association between movement acceleration and subjective age did not hold when including pain and covariates. Drawing from similarities with research on acute exercise, the timing of measures might affect the outcome. Studies have found that physical activity is associated with negative affect immediately after exercise, but if a break is included after the exercise and before the affect measurement, physical activity is associated with positive affect (Reed & Ones 2006).

Pain and its momentary association with subjective age

To the best of our knowledge, no previous studies have examined the relationship between momentary physical activity, pain, and subjective age. On the within-person level, we found a strong association between pain and subjective age, which is in line with previous research (Barrett & Gumber 2020; Booker et al. 2020; Kotter-Grühn et al. 2015). People felt older in moments of more pain than usual, compared to moments with less pain. Pain experience seems to be a bodily reminder of one's age, as bodily pain is associated by many with getting older (Barrett & Gumber 2020). Furthermore, the experience of pain might go along with the experience of stress (Abdallah & Geha 2017), which has consistently been shown to increase subjective age (e.g., (Kornadt et al. 2022)). Future studies should further explore this relationship to investigate whether pain management might be effective in improving subjective aging experiences.

Despite this relation of pain to subjective age, our hypothesis that pain would moderate the relationship between them was not supported. There may be several reasons for this outcome. Moderation by pain might only exist at certain levels of physical activity. Our measures of physical activity were linear in nature, and we could not address potential effects of different intensity levels. Furthermore, we did not assess whether participants interpreted pain as a cause of physical activity (or age), which might be relevant for their interactive relation to subjective age. It is also conceivable that the relation between pain, physical activity, and subjective age is more complex. For instance, pain might be predictive of both activity and subjective age, and when entered together in a model, result as the strongest predictor. Furthermore, pain could also function as a mediator in the relationship between. Physical activity and subjective age. Finally, different aspects of pain, such as whether it is chronic or acute could all play a role in modulating its relationship with both physical activity and subjective age. In future studies, differentiated assessments of both pain and physical activity are warranted to better understand their interactive effect in people's subjective aging experiences.

Limitations and directions for future research

The current study is original in its focus on the momentary objective and subjective experiences and conditions that impact subjective age as people go about their daily lives, and it adds to previous studies linking physical activity and subjective age in long-term studies and in the laboratory. Still, some limitations should be considered when interpreting our findings.

Our sample size was comparatively small, and variability in subjective age was not given for all participants, which limits our ability to detect small and more complex relations like moderation effects. Drawing from the literature of acute exercise and its relation to cognitive measures (Chang et al. 2012), effects seem to be generally rather small. Given that the initial models including movement acceleration revealed a trend of an effect of physical activity on momentary subjective age, future studies should re-visit these associations with larger samples. Our sample was heterogeneous in terms of life situation and physical fitness, however, our study advertisement and wearing the sensor might have prompted people to be more active during the study than usual. Furthermore, the age range was rather narrow. It might be interesting to include a broader age range, especially adding participants in their late sixties and seventies, to see whether the relation of physical activity and the moderating effect of pain might be more pronounced in these groups, when activity might become more strenuous and pain experiences more frequent (Schmidt et al. 2024).

As our study included fixed assessment intervals, we did not have control on how other moments of physical activity could have related to participants' felt age. Future studies should consider measuring momentary subjective age in moments prompted by physical activity to detect higher intensities and more relevant occasions.

Conclusion

Our study highlights many underexplored aspects of subjective age in a sample of adults in late midlife. Physical activity seems to have smaller effects that future studies should consider when deciding on sample sizes and schemes. The experience of pain was robustly associated with higher momentary subjective age. Our study measured physical activity, pain, and subjective age in people's daily life, which might be highly informative for preventive interventions targeted at the adult population.

Appendix

See Tables 4, 5, 6, and 7

Table 4 Multilevel regression analyses predicting momentary subjective age from movement acceleration (20-min interval), pain, interaction term, and covariates

Variable	Model 1		Model 2		Model 3		Model 4		Model 5		Model 6	
	b(SE)	*p*	*b*(SE)	*p*	*b*(SE)	*p*	*b*(SE)	*p*	*b*(SE)	*p*	*b*(SE)	*p*
Within												
Moac20	**−0.81 (0.36)**	0.022	−0.63 (0.36)	0.076	−0.63 (0.36)	0.078	−0.63 (0.36)	0.076	0.44 (2.31)	0.848	0.52 (2.27)	0.819
Pain			**4.62 (1.03)**	<0.001	**4.63 (1.03)**	<0.001	**4.62 (1.03)**	0.000	**5.52 (2.32)**	0.017	**5.58 (2.29)**	0.015
Moderation					− 1.54 (3.91)	0.694			−2.01 (4.13)	0.627	−2.14 (4.05)	0.597
Between												
Moac20							−0.50 (9.47)	0.958	12.66 (15.77)	0.422	26.83 (22.81)	0.240
Pain							**14.82 (3.84)**	0.000	**24.94 (9.72)**	0.010	28.02 (15.92)	0.078
Moderation									−23.05 (19.27)	0.232	−36.52 (33.33)	0.273
BMI											3.64 (2.32)	0.117
MET											**−5.27 (1.92)**	0.006
Age											**−0.31 (0.13)**	0.020
R2within	0.004	0.235	0.053	0.002	0.054	0.002	0.054	0.002	0.083	0.414	0.860	0.409
R2between							0.319	0.001	0.637	0.003	0.819	<0.001

b = unstandardized regression coefficient. SE = standard error. Values significant at $p < .05$ are in bold. Model 1: within-level only with movement acceleration. Model 2: within-level only with movement acceleration and pain. Model 3: within-level only with movement acceleration, pain and moderation. Model 4: two-level model with movement acceleration and pain. Model 5: two-level model with movement acceleration, pain, and moderation. Model 6: two-level model with movement acceleration, pain, moderation, and covariates

Table 5 Multilevel regression analyses predicting momentary subjective age from movement acceleration (30-min interval), pain, interaction term, and covariates

Variable	Model 1		Model 2		Model 3		Model 4		Model 5		Model 6	
	b(SE)	*p*	*b*(SE)	*p*	*b*(*b*(SE)	*p*	*b*(SE)	*p*	*b*(SE)	*p*	*b*(SE)	*p*
Within												
Moac30	**−0.80 (0.33)**	0.017	−0.58 (0.31)	0.065	−0.59 (0.32)	0.067	−0.60 (0.32)	0.064	0.92 (2.15)	0.670	1.01 (2.09)	0.629
Pain			**3.84 (0.95)**	<0.001	**4.63 (1.03)**	<0.001	**4.61 (1.03)**	<0.001	**5.88 (2.18)**	0.007	**5.974(2.13)**	0.005
Moderation					−1.55 (4.25)	0.714			−2.79 (3.83)	0.466	−2.95 (3.71)	0.427
Between												
Moac30							3.58 (10.75)	0.739	20.87 (24.22)	0.389	39.30 (36.79)	0.285
Pain							**15.23 (3.91)**	<0.001	28.73 (15.77)	0.068	35.00 (26.69)	0.190
Moderation									−30.88 (32.11)	0.336	−51.09 (63.70)	0.357
BMI											3.43 (2.17)	0.115
MET											**−591 (2.05)**	0.004
Age											**−0.30 (0.13)**	0.022
R2within	0.004	0.216	0.012	0.027	0.053	0.003	0.054	0.003	0.104	0.379	0.110	0.361
R2between							0.333	0.001	0.728	0.012	0.910	<0.001

b = unstandardized regression coefficient. SE = standard error. Values significant at $p < 0.05$ are in bold. Model 1: within-level only with movement acceleration. Model 2: within-level only with movement acceleration and pain. Model 3: within-level only with movement acceleration, pain, and moderation. Model 4: two-level model with movement acceleration and pain. Model 5: two-level model with movement acceleration, pain, and moderation. Model 6: two-level model with movement acceleration, pain, moderation, and covariates

Table 6 Multilevel regression analysis predicting momentary subjective age with step count (20-min interval), pain, the interaction term, and covariates

Variable	Model 1		Model 2		Model 3		Model 4		Model 5		Model 6	
	b(SE)	*p*	*b*(SE)	*p*	*b*(SE)	*p*	*b*(SE)	*p*	*b*(SE)	*p*	*b*(SE)	*p*
Within												
Steps20	−0.14 (0.13)	0.276	−0.10 (0.13)	0.462	−0.10 (0.13)	0.463	0.10 (0.13)	0.465	0.45 (0.85)	0.597	0.46 (0.84)	0.580
Pain			**4.65 (1.03)**	< 0.001	**4.66 (1.03)**	< 0.001	**4.65 (1.03)**	< 0.001	**6.30 (2.90)**	0.030	**6.34 (2.87)**	0.027
Moderation					0.10 (1.53)	0.950			−1.05 (1.56)	0.501	−1.08 (1.54)	0.485
Between												
Steps20							2.41 (6.51)	0.711	5.94 (7.41)	0.422	12.09 (8.12)	0.136
Pain							**15.04 (3.75)**	< 0.001	**23.73 (7.36)**	< 0.001	**26.12 (12.29)**	0.034
Moderation									−5.25 (3.90)	0.178	−8.74 (7.19)	0.224
BMI											4.12(2.52)	0.102
MET											**−5.35 (2.00)**	0.007
Age											**−0.29 (0.13)**	0.025
R2within	0.000	0.706	0.051	0.006	0.051	0.006	0.053	0.006	0.062	0.157	0.117	0.403
R2between							0.362	0.001	0.915	0.106	0.784	< 0.001

b = unstandardized regression coefficient. SE = standard error. Values significant at $p < 0.05$ are in bold. Model 1: within-level only with step count. Model 2: within-level only with step count and pain. Model 3: within-level only with step count, pain, and moderation. Model 4: two-level model with step count and pain. Model 5: two-level model with step count, pain, and moderation. Model 6: two-level model with step count, pain, moderation, and covariates

Table 7 Multilevel regression analysis predicting momentary subjective age with step count (30-min interval), pain, the interaction term, and covariates

Variable	Model 1		Model 2		Model 3		Model 4		Model 5		Model 6	
	b(SE)	*p*	*b*(SE)	*p*	*b*(SE)	*p*	*b*(SE)	*p*	*b*(SE)	*p*	*b*(SE)	*p*
Within												
Steps30	−0.09 (0.12)	0.450	−0.03 (0.12)	0.819	−0.03 (0.12)	0.811	−0.03 (0.12)	0.805	0.08 (0.41)	0.842	0.11 (0.41)	0.778
Pain			**4.66 (1.03)**	< 0.001	**4.66 (1.03)**	< 0.001	**4.66 (1.03)**	< 0.001	**5.03 (1.69)**	0.003	**5.14 (1.70)**	0.002
Moderation					0.34 (1.43)	0.811			−0.21 (0.78)	0.787	−0.27 (0.78)	0.730
Between												
Steps30							5.86 (7.02)	0.404	17.06 (36.81)	0.643	**25.12 (12.20)**	0.039
Pain							**15.49 (3.81)**	< 0.001	47.12 (104.73)	0.653	60.52 (32.75)	0.065
Moderation									−16.35 (53.33)	0.759	−24.95 (16.71)	0.135
BMI											2.55 (1.92)	0.185
MET											**− 6.41 (2.00)**	0.002
Age											**− 0.34 (0.12)**	0.004
R2within	0.000	0.706	0.051	0.006	0.051	0.006	0.053	0.006	0.062	0.157	0.065	0.162
R2between							0.362	0.001	0.915	0.106	0.992	< 0.001

b = unstandardized regression coefficient. SE = standard error. Values significant at $p < 0.05$ are in bold. Model 1: within-level only with step count. Model 2: within-level only with step count and pain. Model 3: within-level only with step count, pain and moderation. Model 4: two-level model with step count and pain. Model 5: two-level model with step count, pain, and moderation. Model 6: two-level model with step count, pain, moderation, and covariates

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Availability of data and materials Syntaxes and outputs from the analysis are available: https://osf.io/bns2z/?view_only=38a13ef8e05f44a991346d10680404ff.

Declarations

Competing interest We have no conflict of interest to disclose.

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