Heliyon 10 (2024) e29969

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Characteristics of cadence during continuous walking in daily life

Kunihiro Shiina [a,*], Atsushi Nakagomi [a], Chisato Mori [a], Kenichi Sakurai [a], Takahiro Tabuchi [b]

[a] *Center for Preventive Medical Science, Chiba University, Chiba, 263-8522, Japan*
[b] *Department of Cancer Epidemiology, Osaka International Cancer Institute Cancer Control Center, Osaka, 540-0008, Japan*

ARTICLE INFO

Keywords:
Cadence
Continuous walking
Walking speed
Health
Japan

ABSTRACT

Despite the acknowledged relationship between the usual (preferred) walking speed (UWS) and health, there is currently no practical method available to reliably and accurately detect slight changes in UWS. This study aimed to explore whether either of the following two phenomena occurs during continuous daily walking in various periods: (a) Similarity between the most frequent cadences in the two periods. (b) The occurrence of the most frequent cadence in at least one of the two periods during the other period, with a frequency close to that of the most frequent cadence. In August 2021, invitations to participate in the study were extended via email to participants that took part in the Japan COVID-19 and Society Internet Surveys (JACSIS). A mobile phone application that collected step data during continuous walking was provided to the participants, and data were collected from December 1, 2021, to January 31, 2022. While 1022 participants installed the phone application, only 505 had measurement data for ten days or more in each of the two months of the study duration. The cadence during continuous walking was automatically measured daily from 05:00 to 21:00. Most participants exhibited at least one of the phenomena mentioned above, confirming a common, notably frequent, invariant cadence over time. Overall, this method allows for the identification of minor reductions and lower bounds of decline in UWS. This study illustrates the potential for tracking a decreasing trend in UWS. Early detection of a downward trend permits individuals to take timely remedial action, as recovery is relatively easy, and the confirmation of even a slight recovery bolsters recovery motivation.

1. Introduction

As individuals age, there is a tendency to gradually decrease their usual walking speed (UWS), also known as preferred walking speed [1], due to the declining walking ability associated with aging [2,3]. However, considerable differences exist among individuals' experiences. UWS has been strongly linked to physical health and mortality in numerous studies [4–17]. In the majority of these studies, speed has either been assessed through self-reporting instruments or by conducting empirical studies where participants demonstrate their ability to walk a short distance at their usual pace.

Particularly for individuals in the middle-aged group or those in the pre-frail* stage, changes in UWS tend to be gradual. Here, middle age refers to the period from about 40 to 60 years old, and pre-frail refers to the stage before becoming frail.

As a result, a measurement method that can accurately detect a slight annual rate of change in people's UWS is desirable for early

* Corresponding author. Center for Preventive Medical Science, Chiba University 1-33 Yayoicho, Inage-ku, Chiba, 263-8522, Japan.
E-mail address: shiina@kjd.co.jp (K. Shiina).

https://doi.org/10.1016/j.heliyon.2024.e29969
Received 25 July 2023; Received in revised form 16 April 2024; Accepted 18 April 2024
Available online 3 May 2024

identification and intervention and to motivate them by affirming the possibility of recovering their walking speeds. However, as the walking speed diminishes, the changes occur gradually and are difficult to measure; thus, minimizing the measurement error becomes highly important. Among the existing measurement methods, many exhibit error margins that are too large to precisely capture subtle changes in walking speed. For example, in a scenario where an actual speed change of −3% occurs, and the ratio of the standard error to the speed (SE-coefficient) is 2 % at both the beginning and end of the measurement period, and the error is according to a normal distribution, the measured value change is likely to fall between −6% and 0 %, with a relatively high chance of being positive. This implies that the measurement results are unreliable when the goal is to detect minor changes.

Notably, while measuring the walking speed, even if individuals attempt to walk at their UWS, the bias associated with their awareness of the measurement cannot be eliminated, and the deviation between the actual UWSs and measured values cannot be estimated [18]. Additionally, variations in the physical conditions, temperature, and other walking environments between the beginning and end of the measurement period contribute to the challenges experienced. Moreover, the limited number of daily measurements adds to the complexity, making it challenging to achieve an SE coefficient of <2 % (Supplement 3).

The walk ratio is a coefficient defined as the ratio of step length to cadence, reported to remain constant during continuous walking, even as the walking ability remains unchanged [19–25]. Walking speed can be calculated by multiplying the step length by cadence. When the walk ratio is constant, the walking speed becomes proportional to the square of the cadence. In the context of this study, walking will be exclusively referred to as 'continuous walking.'

Consequently, the cadence at the most frequent walking speed (MFWS) is distinctive due to a constant walk ratio. In the context of this study, this cadence is referred to as the most frequent cadence (MFC). Similarly, the cadence during UWS is also unique and is subsequently referred to as the usual walking cadence (UWC) in this study.

As cadence declines, the walk ratio either remains constant or decreases; if it increases, this implies the step length increases when walking at the same cadence. However, research has shown that such occurrences are unlikely [26]. Therefore, changes in the UWS and MFWS can be detected by changes in the UWC and MFC.

To effectively detect the trend of a slight change in an index, the fluctuation of the index and SE of the measured values must be minimal. To apply this principle to UWC, both the usual fluctuation of UWC and the SE of the UWC measurement method need to be small.

We could not find any prior studies on the frequencies or fluctuations in UWS, we presumed that UWS occurs frequently in daily life and typically maintains a stable value due to its inherent nature. If UWS occurs frequently and maintain a stable value, there should be a notable frequent cadence. To verify the presence of notable frequent cadence that is invariant over time in daily life, the following conditions were assumed for two different non-overlapping time periods, A and B.

1) When both MFWSs were UWSs, and both MFCs were UWCs, the probability that the MFCs in periods A and B were similar was high.
2) If the MFWS was UWS in Period A but not in Period B, and if walking speeds close to those of the UWS in Period A also frequently occurred in Period B, cadences close to the MFC in Period A also frequently occurred in Period B.
3) When both the MFWSs are not UWS, their relationship may be weak.

Thus, in this study, the following hypotheses were tested, involving the occurrence of one of the following two phenomena observed in the participants' measured values during the two periods.

1) The MFCs of the two periods are close.
2) The MFC in at least one of the two periods also occurred in the other period at a frequency close to that of the MFC in that period.

However, it is important to acknowledge that several confounders may have been present due to health conditions, and external factors may have changed between the two periods.

Nevertheless, if we assume that the standard error of the MFC measurements is large, significant fluctuations will occur in the measurements, thereby increasing the probability that the MFCs will not be close at different periods. Consequently, the probability of observing these two Phenomena would be low. If this hypothesis is substantiated, it implies that the SE of the measurement is small.

However, if either of these two phenomena is observed in the majority of the participants, it confirms the presence of a notably frequent cadence that remains constant over time. As this distinctive cadence diminishes with aging over an extended period, the changes in cadence enable the detection of changes in UWS. We believe that utilizing these observed phenomena for detecting speed changes would enhance the applicability of the existing academic knowledge regarding the relationship between walking speed and health, which will be more beneficial for people's health by enabling the detection of speed changes over time.

2. Materials and methods

2.1. Ethics

The present study adhered to the principles of the Declaration of Helsinki and was approved by the appropriate ethics committee of Chiba University (approval number: 2493, June 2, 2021). All participants provided written informed consent.

This research was conducted as an adjunct study to the main nationwide Japan COVID-19 Society Internet Surveys (JACSIS: 30,000 participants, 18–79 years old). Participants were recruited from the JACSIS study. In August 2021, invitations to participate in the study were extended to JACSIS participants via email, and 1022 individuals agreed to participate. Participation criteria was 20 years of age or older.

The protocol and aim of this study were clearly communicated to the respondents, who, in turn, provided written consent to participate. As an appreciation for their involvement, each participant was offered an incentive of 500 JPY (approximately 4 USD).

2.2. Study period

The study was conducted during the following periods: December 1–28, 2021 and January 4–31, 2022. The interval between December 29, 2021, and January 3, 2022, was excluded because it coincided with the New Year holidays when everyday routines were likely to be disrupted.

2.3. Cadence data collection method

We developed an application for iPhone devices that calculates the cadence from stored information based on the number of steps.

As iPhone devices automatically record step counts taken at different times during the day, when participants opened the designed application, their devices automatically calculated the cadence distribution for five days using their time-specific step count information, and the derived information is transmitted to the server.

Notably, the participants were not involved in the calculation process. To prevent overburdening the application, the calculation specifically focused on the steps taken between 5:00 and 21:00.

2.4. Summary of participants and criteria

Out of the 1022 participants who downloaded the application, 761 provided measurement data for both December and January. Among them, 505 participants had data available for at least ten days during both months. Ultimately, the data from 505 participants were included in this study.

2.5. Definition of the continuous walking segment and cadence

For this study, the number of steps taken in 15 s (s) was used as the measurement unit. A continuous walking segment lasting 15 s with a constant cadence was defined as three consecutive 5-s step counts between 5:00 and 21:00, satisfying the condition outlined below.

From the three consecutive 5-s step counts (A, B, and C), only the 15-s step counts were extracted where the absolute values of A-B, B–C, and C-A were within 1.

This condition ensured that the gait cycle remained within a specified range for 15 s, defining it as a continuous walking segment with a constant cadence. Thus, all data collected during this study exhibited a constant cadence (Supplement 1).

Notably, when the cadence in the UWS drops to $\leq$100 steps/min, the impact of the decrease in stride on walking speed becomes more pronounced [19,21]. Therefore, the significance level was set at $>$ 100 steps/min. Additionally, maintaining body balance was considered challenging at a constant cadence of $\leq$80 steps/min for over 15 s in daily life (even though such instances were rare) [19,27]. As a result, participants with cadences falling below this threshold were excluded from the study.

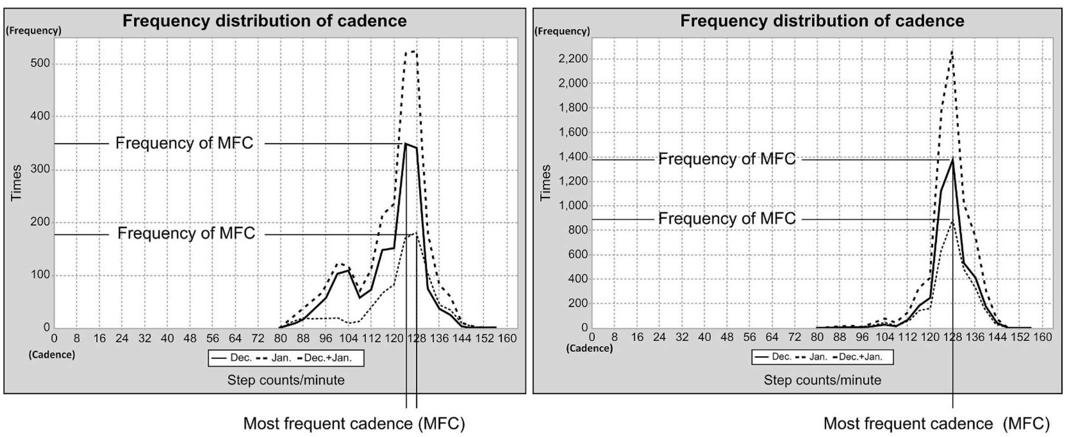

Fig. 1. Explanation of Most Frequent Cadence (MFC) and Frequency of MFC Vertical axis: number of measurements (frequency). Horizontal axis: cadence (steps/minute) Solid line: December; Dotted line: January; Dashed line: December and January.

2.6. Verification of step count for 15 s

The step-count accuracy for 15 s during continuous walking, as defined in Section 2.5, was assessed using the actual step-count information measured with a timer (as the gold standard). The total number of samples taken was 118, and the range of actual steps recorded in 15 s varied from 22 to 35 steps. The absolute difference between the terminal measurement value and the actual step counts for 15 s was as follows: 66 samples had no difference, 46 samples had a difference of 1, 6 samples had a difference of 2, and there were no samples with a difference of 3 or more. The difference between the means of these measurements was 0.7 % (Supplement 2 and Fig. S1). The intracorrelation coefficient (1,1) was 0.974, and the standard deviation of the difference between the iPhone measurement value and the actual step count was 0.773 (equivalent to 2.8 % for an average of approximately 27.3 steps).

In accordance with the normal distribution, it was determined that 99 % of the measurements fell within 2.58 times the variance, which, for an average of approximately 27.3 steps, equated to 7.1 %. Based on this, the required sample size was calculated to be 106.

Given that the application calculates thousands of 15 s intervals daily, even if the threshold was exceeded in one interval, the subsequent 15 s interval within the threshold was captured. Consequently, the distribution of cadences using a 15 s step count accurately reflected how the actual cadences were distributed. Importantly, it is worth noting that the iPhone terminal measurement of step count was validated to be precise during continuous walking with a constant gait cycle, and the step-count accuracy was very low when the fluctuation of the gait cycle was significant.

2.7. Definition of most frequent cadence (MFC)

Fig. 1 illustrates two samples of cadence distribution over two months. The MFCs were defined as the most frequently occurring cadences each month, as shown in Fig. 1. The unit of distribution was four steps/minute.

In the left graph, the participant generally walked at a cadence ranging from 124 to 128 steps/min across both months, occasionally walking with a cadence falling in the middle of that range. On the right, the graph depicts a participant who consistently walked at a cadence rate of 128 steps/min in both December and January.

While the actual MFC was a continuous number, the data in this study represent the actual cadence substituted in units of four steps/minute, introducing an error due to the unit of four steps/minute.

2.8. Analysis method

The testing of the hypothesis that the MFC represents the most frequent actual cadence involved the following procedure.

1. Defining the requirement that satisfies the hypothesis using MFC.
2. Identifying participants who met the criteria based on the defined requirement.
3. Testing the hypothesis by evaluating the proportion of the 505 participants who met the criteria.

3. Results

3.1. Data overview

On average, one-third to one-half of the total daily steps were recorded as continuous walking. Table 1 presents an overview of all measurements.

With thousands of measurements taken over four weeks, the SE of the measurements was significantly reduced. Particularly, the frequency of cadence occurrence both before and after MFC exceeded 52 % in all measurements, indicating that a specific cadence occurred frequently.

Table 1
Data overview.

Attributes of participants (age)	116: 20s, 141: 30s, 126: 40s, 68: 50s, 39: 60s, 6: 70s, 9 were adults and did not disclose their age.		
Attributes of participants (gender)	258: men, 239: women, 8 chose not to reveal their gender.		
Item	December 1st – 28th	January 4th – 31st	Unit
Mean of measured days	18	20	Days
Steps per day	6373 ± 3564	6282 ± 3949	steps/day
Number of measurements per day	258 ± 175	260 ± 211	times/person
Number of measurements in 4 weeks	4829	5337	times/person
Mean frequency of MFC in 4 weeks	1121	1250	times/person
Mean frequency of (MFC – 4 steps/minute)	728	833	times/person
Mean frequency of (MFC + 4 steps/minute)	681	740	times/person
Rate of the above 3 frequencies	52.3	52.9	%

3.2. MFC characteristics and requirements definition

1. The absolute value of the difference in MFC between both months was 3.72 ± 5.95 steps/minute. This indicates that for most participants, the MFC occurred within a limited range of 4 steps/minute in both months. In other words, most people walked at similar cadences during both months.
2. The frequency in January of the same cadence as MFC in December divided by the frequency of MFC in January was 88.5 % ± 18.3 %, and similarly, the frequency in December of the same cadence as MFC in January divided by the frequency of MFC in December was 88.2 % ± 19.2 %. These results showed that although the MFC in one month differed from those in the other months, most participants experienced a cadence equal to the MFC in both months.

These two phenomena, despite being distinct, support our hypothesis. Based on the above mean and SD calculated values, the inclusion criteria for participants were as follows.

Definition 1. The absolute difference in MFC between both months was within 4 steps/min, less than mean + SD divided by 2. This increment was the smallest for all measurements.

Definition 2. The frequency of the same cadence as the MFC in one month was ≥79 % of the MFC frequency in the other month, equal to mean−SD divided by 2. This rate is considered sufficiently close to support Hypothesis 2.

Participants who observed at least one of these phenomena were selected, and the hypothesis was tested with a proportion of the 505 participants.

3.3. Validation

From the wide distribution of the MFC ranging from 84 to 140 steps/min, 391 participants were categorized under Definition 1, with an absolute difference of 4 steps/minute, and 445 participants were categorized under Definition 2 (over 79 %). Excluding duplicates, a total of 461 participants (91.28 %) out of the 505 met either Definition 1 or 2, as illustrated in Figs. 2 and 3.

For the 44 participants who did not fit either definition, the number of measurements for at least one month was considered negligible in 8. Furthermore, based on the probability of 91.28 % and the sample size of 505, the population existence probability was estimated to be 91.28 % ± 2.46 % (95 % CI). Thus, based on our calculations, with a probability of 91.28 %, the required number of samples is 488, which we considered sufficient for a large majority. Therefore, this hypothesis was validated.

Additional validation using the Kernel Density Estimation yielded similar results (Figs. 4 and 5). A total of 374 participants fell under Definition 1, and 456 participants fell under Definition 2. Excluding duplicates, 462 (91.45 %) of the 505 participants fell under Definitions 1 or 2, further validating the hypothesis for most participants.

4. Discussion

4.1. Early change detection

Definitions 1 and 2 in Section 3.2 were deemed sufficiently stringent for verification, and our results confirmed the presence of a notably frequent cadence that remained invariant over time. This characteristic facilitated the detection of small changes in the UWS in daily life through a large number of measurements. However, it is important to note that while these definitions were robust for verification, certain exceptions were inevitable.

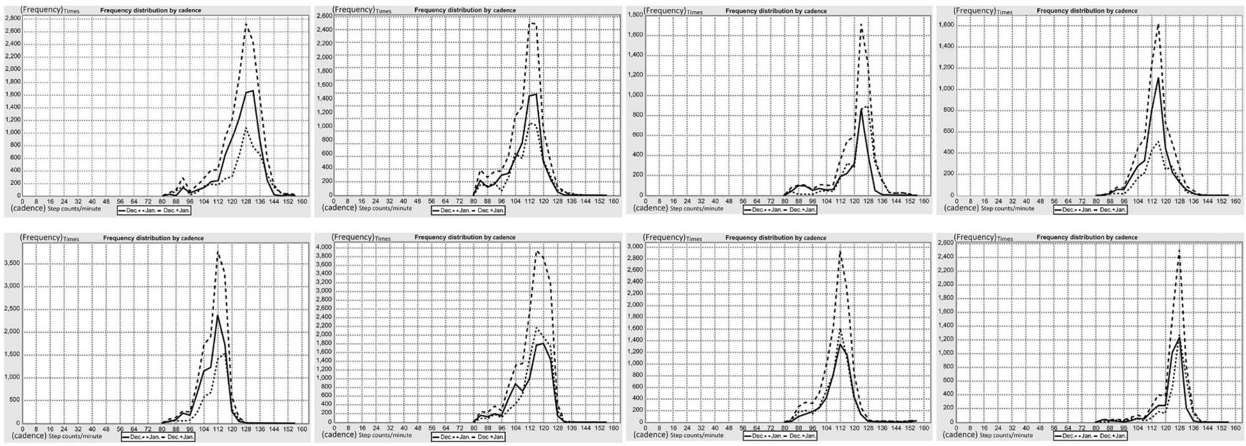

Fig. 2. Cases of Definition 1 (8 samples, 391 participants) Solid line: December; Dotted (thin) line: January; Dashed line: December and January.

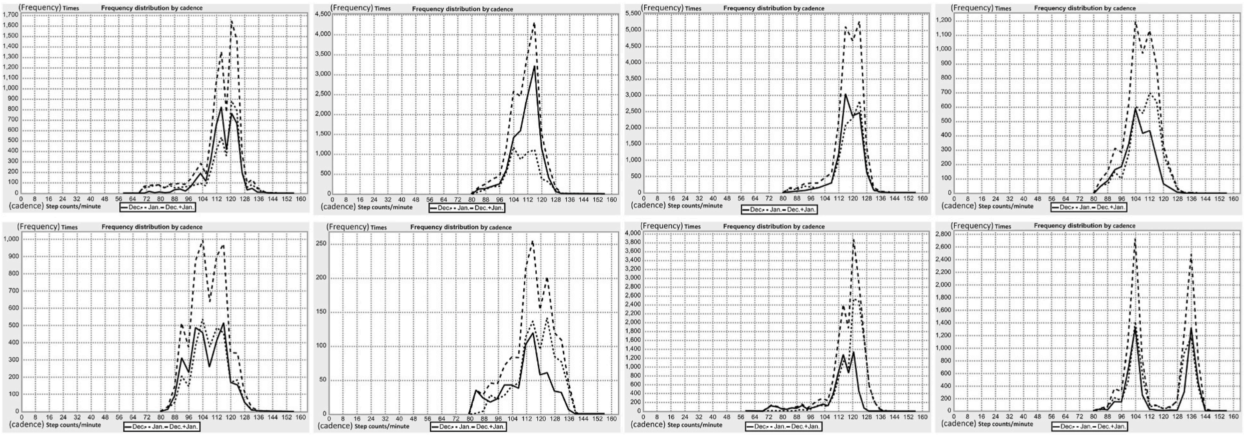

Fig. 3. Cases of Definition 2 (8 samples, 445 participants) Solid line: December; Dotted (thin) line: January; Dashed line: December and January.

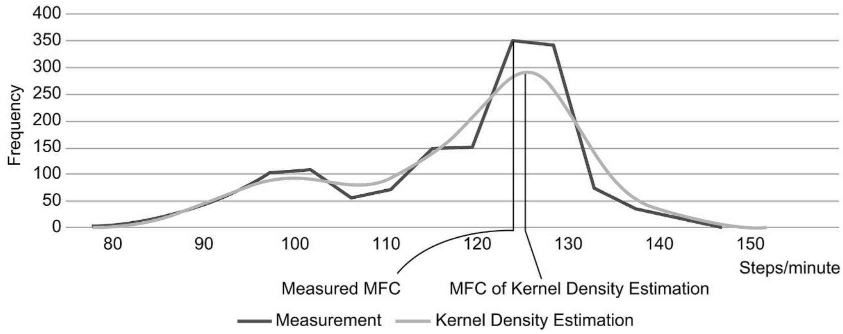

Fig. 4. Sample of measurement dispersion and kernel density estimation.

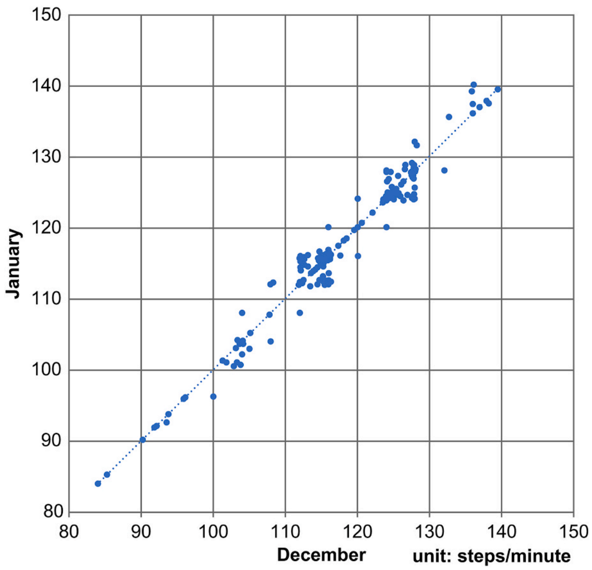

Fig. 5. Results of Definitions 1 and 2 using Kernel Density Estimation (462 participants).

Under these conditions, our findings indicated that the fluctuation over time and SE of the MFC were both minimal. In Definition 1, where the MFCs of both periods are similar, these values can be reliably identified as the UWC with a high probability. Similarly, in Definition 2, the applicable MFC can also be identified as a UWC with a high probability. Thus, we considered that frequent UWSs during continuous walking may have caused these unknown phenomena; otherwise, an alternative UWS would have been required. Moreover, they were observed repeatedly during long-term measurements.

Furthermore, while MFC may sometimes differ from UWC, such as when walking with companions or during consciously brisk walking, such as in the case of exercise habits, if these two phenomena are repeatedly observed in long-term measurements, UWCs can be identified with a high probability across many MFCs, allowing the tracking of their transitions.

Changes from the non-frail to pre-frail* stages result in reduced cadence, with prominent parameters for the latter stage, including reduced cadence and increased step-width variability [26–28]. The UWC, typically around 120 steps/min when healthy, declines to $<$100 steps/min during aging. During this time, the MFC also decreases from approximately 120 steps/min to $\leq$100 steps/min, allowing the aging process to be traced.

The change in the UWS is the squared change in the UWC multiplied by the change in the walk ratio. Assuming that the walk ratio is constant or decreases when the UWC falls, the rate of change of the square of the UWC indicates the lower bound of the decline in UWS. Particularly, when a slight decline in UWC can be detected numerically, which occurs often in the early stage, it allows for the detection of a UWS slowdown in the early stage. What makes this possible is the existence and identification of a notably frequent cadence that remains unchanged over a period of time.

4.2. Limitations

This study has some limitations. First, despite validating this hypothesis, it is important to acknowledge that there may be cases in which both MFCs with similar values are not necessarily equal to the UWC. Second, this study did not track the progression of decreased cadence over time, and therefore, the feasibility of this hypothesis should be further confirmed in future studies with larger sample sizes and long-term data.

5. Conclusions

This study demonstrated the possibility of tracing a decrease in UWS, amidst considerable variability in individuals. Furthermore, the early detection of a downward trend in UWS provides individuals with advanced notice when recovery is still relatively easy. Additionally, we found that confirming even slight recovery contributes to maintaining motivation for rehabilitation efforts.

* We considered middle age to be between the ages of 40 and 60, as described in Britannica, although, the age period is somewhat arbitrary, differing greatly from person to person. The definition of pre-frail stage follows from reference [27], which is according to the study "Early identification of frailty: Developing an international delphi consensus on pre-frailty".

Ethical approval

The present study was conducted in accordance with the principles of the Declaration of Helsinki and was approved by the appropriate ethics committee of Chiba University (approval number: 2493). All the participants provided written informed consent.

Data availability statement

The data (373 MB) associated with our study is presently not available in a public repository. However, the data will be made available on request.

Funding

This work was supported by the Center for Preventive Medical Science, Chiba University and Grants from the ChibaFoundation for Health Promotion & Disease Prevention. The funding sources played no role in the study design, data collection, analysis, decision to publish, or manuscript preparation.

CRediT authorship contribution statement

Kunihiro Shiina: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Atsushi Nakagomi:** Supervision, Resources, Investigation. **Chisato Mori:** Supervision, Project administration, Funding acquisition. **Kenichi Sakurai:** Supervision. **Takahiro Tabuchi:** Investigation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Kunihiro Shiina reports was provided by Chiba University. Chisato Mori, Kenichi Sakurai, Atsushi Nakagomi reports a relationship with Chiba University that includes: employment. Kunihiro Shiina has patent #Patent No. 6774579 (Japan) licensed to Kunihiro Shiina. Nothing If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We thank Rakuten Insight, Inc., for their cooperation in recruiting participants, obtaining their consent to participate, and distributing the application. We also thank the Center for Preventive Medicine Sciences, Chiba University, for the opportunity to conduct this study.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e29969.

References

[1] S.J. Wickler, D.F. Hoyt, E.A. Cogger, M.H. Hirschbein, Preferred speed and cost of transport: the effect of incline, J. Exp. Biol. 203 (2000) 2195–2200, https://doi.org/10.1242/jeb.203.14.2195.

[2] K. Tainaka, J. Aoki, Fitness-related factors associated with changes in walking speed in elderly women, Phys. Fit. Sci. 51 (2002) 245–251, https://doi.org/10.7600/jspfsm1949.51.245 (in Japanese).

[3] T. Ikezoe, Age-related change in motor function, Phys. Ther. 48 (2021) 446–452, https://doi.org/10.15063/rigaku.48-4kikaku_Ikezoe_Tome (in Japanese).

[4] Q. Sun, M.K. Townsend, O.I. Okereke, O.H. Franco, F.B. Hu, F. Grodstein, Physical activity at midlife in relation to successful survival in women at age 70 years or older, Arch. Intern. Med. 170 (2010) 194–201, https://doi.org/10.1001/archinternmed.2009.503.

[5] S. Studenski, S. Perera, K. Patel, C. Rosano, K. Faulkner, M. Inzitari, et al., Gait speed and survival in older adults, JAMA 305 (2011) 50–58, https://doi.org/10.1001/jama.2010.1923.

[6] P.C. Dempsey, C. Musicha, A.V. Rowlands, M. Davies, K. Khunti, C. Razieh, et al., Investigation of a UK Biobank cohort reveals causal associations of self-reported walking pace with telomere length, Commun. Biol. 5 (2022) 381, https://doi.org/10.1038/s42003-022-03323-x.

[7] M. Cesari, S.B. Kritchevsky, B.W.H.J. Penninx, B.J. Nicklas, E.M. Simonsick, A.B. Newman, et al., Prognostic value of usual gait speed in well-functioning older people—results from the health, aging and body composition study, J. Am. Geriatr. Soc. 53 (2005) 1675–1680, https://doi.org/10.1111/j.1532-5415.2005.53501.x.

[8] L.J.H. Rasmussen, A. Caspi, A. Ambler, J.M. Broadbent, H.J. Cohen, T. d'Arbeloff, et al., Association of neurocognitive and physical function with gait speed in midlife, JAMA Netw. Open 2 (2019) e1913123, https://doi.org/10.1001/jamanetworkopen.2019.13123.

[9] A.P. McGinn, R.C. Kaplan, J. Verghese, D.M. Rosenbaum, B.M. Psaty, A.E. Baird, et al., Walking speed and risk of incident ischemic stroke among postmenopausal women, Stroke 39 (2008) 1233–1239, https://doi.org/10.1161/STROKEAHA.107.500850.

[10] S. Hayes, J.F. Forbes, C. Celis-Morales, J. Anderson, L. Ferguson, J.M.R. Gill, et al., Association between walking pace and stroke incidence: findings from the UK Biobank Prospective Cohort Study, Stroke 51 (2020) 1388–1395, https://doi.org/10.1161/STROKEAHA.119.028064.

[11] Z. Meiner, E. Ayers, J. Verghese, Motoric cognitive risk syndrome: a risk factor for cognitive impairment and dementia in different populations, Ann. Geriatr. Med. Res. 24 (2020) 3–14, https://doi.org/10.4235/agmr.20.0001.

[12] E. Ayers, J. Verghese, Diagnosing motoric cognitive risk syndrome to predict progression to dementia, Neurodegener. Dis. Manag. 4 (2014) 339–342, https://doi.org/10.2217/nmt.14.39.

[13] J. Verghese, E. Ayers, N. Barzilai, D.A. Bennett, A.S. Buchman, R. Holtzer, et al., Motoric cognitive risk syndrome: multicenter incidence study, Neurology 83 (2014) 2278–2284, https://doi.org/10.1212/WNL.0000000000001084. https://n.neurology.org/content/83/24/2278.

[14] R.A. Hackett, H. Davies-Kershaw, D. Cadar, M. Orrell, A. Steptoe, Walking speed, cognitive function, and dementia risk in the English longitudinal study of ageing, J. Am. Geriatr. Soc. 66 (2018) 1670–1675, https://doi.org/10.1111/jgs.15312.

[15] T. Buracchio, H.H. Dodge, D. Howieson, D. Wasserman, J. Kaye, The trajectory of gait speed preceding mild cognitive impairment, Arch. Neurol. 67 (2010) 980–986, https://doi.org/10.1001/archneurol.2010.159.

[16] E. Yoon, S. Bae, H. Park, Gait speed and sleep duration is associated with increased risk of mci in older community-dwelling adults, Int. J. Environ. Res. Public Health 19 (2022) 7625, https://doi.org/10.3390/ijerph19137625.

[17] F.A.A. Masse, J.H. Ansai, E. Fiogbe, P.G. Rossi, A.C.G. Vilarinho, A.C.M. Takahashi, et al., Progression of gait changes in older adults with mild cognitive impairment: a systematic review, J. Geriatr. Phys. Ther. 44 (2021) 119–124, https://doi.org/10.1519/JPT.0000000000000281.

[18] J.M. Van Ancum, K.S. van Schooten, N.H. Jonkman, B. Huijben, R.C. van Lummel, C.G.M. Meskers, et al., Gait speed assessed by a 4-m walk test is not representative of daily-life gait speed in community-dwelling adults, Maturitas 121 (2019) 28–34, https://doi.org/10.1016/j.maturitas.2018.12.008.

[19] H. Nagasaki, Stability limits of natural gait, J. Soc. Biomech. 30 (2006) 115–118, https://doi.org/10.3951/sobim.30.115 (in Japanese).

[20] V. Rota, L. Perucca, A. Simone, L. Tesio, Walk ratio (step length/cadence) as a summary index of neuromotor control of gait: application to multiple sclerosis, Int. J. Rehabil. Res. 34 (2011) 265–269, https://doi.org/10.1097/MRR.0b013e328347be02.

[21] R. Murakami, Y. Otaka, Estimated lower speed boundary at which the walk ratio constancy is broken in healthy adults, J. Phys. Ther. Sci. 29 (2017) 722–725, https://doi.org/10.1589/jpts.29.722.

[22] U. Lindemann, L. Schwickert, C. Becker, M. Gross, R. Nolte, J. Klenk, Estimate of gait speed by using persons' walk ratio or step-frequency in older adults, Aging Clin. Exp. Res. 33 (2021) 2989–2994, https://doi.org/10.1007/s40520-021-01832-z.

[23] S.K. Huber, R.H. Knols, J.P.O. Held, T. Christen, E.D. de Bruin, Agreement, reliability, and concurrent validity of an outdoor, wearable-based walk ratio assessment in healthy adults and chronic stroke survivors, Front. Physiol. 13 (2022) 857963, https://doi.org/10.3389/fphys.2022.857963.

[24] B. Bogen, R. Moe-Nilssen, A.H. Ranhoff, M.K. Aaslund, The walk ratio: investigation of invariance across walking conditions and gender in community-dwelling older people, Gait Posture 61 (2018) 479–482, https://doi.org/10.1016/j.gaitpost.2018.02.019.

[25] N. Sekiya, H. Nagasaki, Reproducibility of the walking patterns of normal young adults: test-retest reliability of the walk ratio(step-length/step-rate), Gait Posture 7 (1998) 225–227, https://doi.org/10.1016/S0966-6362(98)00009-5.

[26] M. Schwenk, C. Howe, A. Saleh, J. Mohler, G. Grewal, D. Armstrong, et al., Frailty and technology: a systematic review of gait analysis in those with frailty, Gerontology 60 (2014) 79–89, https://doi.org/10.1159/000354211.

[27] D.P.P. Pradeep Kumar, N. Toosizadeh, J. Mohler, H. Ehsani, C. Mannier, K. Laksari, Sensor-based characterization of daily walking: a new paradigm in prefrailty/frailty assessment, BMC Geriatr. 20 (2020) 164, https://doi.org/10.1186/s12877-020-01572-1.

[28] A. Apsega, L. Petrauskas, V. Alekna, K. Daunoraviciene, V. Sevcenko, A. Mastaviciute, et al., Wearable sensors technology as a tool for discriminating frailty levels during instrumented gait analysis, Appl. Sci. 10 (2020) 8451, https://doi.org/10.3390/app10238451.