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Digital Twin and Wearables Unveiling Pedestrian Comfort Dynamics and Walkability in Cities

Marcel Ignatius[1,2], Joie Lim[2], Ben Gottkehaskamp[2,3], Kunihiko Fujiwara[1,4], Clayton Miller[2], Filip Biljecki[1,5]

[1] Department of Architecture, National University of Singapore, Singapore - (m.ignatius, kunihiko, filip)@nus.edu.sg
[2] Department of the Built Environment, National University of Singapore, Singapore - (m.ignatius, joie.lim)@nus.edu.sg, e1237518@u.nus.edu, clayton@nus.edu.sg
[3] Chair of Building Technology and Climate Responsive Design, TUM School of Engineering and Design, Technical University of Munich, Germany – Ben.Gottkehaskamp@tum.de
[4] Research & Development Institute, Takenaka Corporation, Japan – fujiwara.kunihiko@takenaka.co.jp
[5] Department of Real Estate, National University of Singapore, Singapore

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Abstract

This research examines the interplay of outdoor thermal comfort, walkability, and three-dimensional geospatial landscape within cities. Employing advanced data collection methods, including smart wearables and street view imagery (SVI), we conduct a comprehensive exploration of integrating heterogeneous sensor data and computer vision in an urban digital twin (UDT) we develop. We focus on the integrated thermal walk concept, where participants, equipped with wearables, contribute health metrics and real-time thermal sensation feedback while walking along selected routes for which we collect detailed 3D geoinformation, which in turn provides a foundation for understanding and improving comfort and walkability in cities. Our study not only addresses the integration, but also underscores the transformative role of advanced analytics and UDT in deciphering how urban morphology influences thermal experiences. While the growing accessibility of wearable devices facilitates work such as ours, we highlight challenges in collecting diverse participant data and the imperative need for specialized expertise in UDT and computer vision. This research contributes to (1) digital twins, providing a novel combination of data integration and a new use case, and to (2) urban climatology, advancing our understanding of the relationship among microclimate, urban environment, and outdoor thermal comfort. Beyond theoretical contributions, the study's practical significance is revealed in the development of accurate predictive models for understanding walkability, promising improvements in the quality of urban life, and pronouncing the important role of 3D geoinformation in such a domain.

1. Introduction

1.1 Background and Motivation

The integration of advanced 3D geoinformation technologies and the concept of urban digital twins (UDT) introduces an era of unprecedented insight into the intricate dynamics of cityscapes, supporting urban studies and management of smart cities. UDT marks a significant evolution from the traditional Smart City concept, embodying several key dimensions. Firstly, they entail integrated and intelligent systems designed for comprehensive city management. This concept involves the assimilation of heterogeneous data, ranging from sensor inputs to citizen engagement, all orchestrated through multidisciplinary optimization approaches (Ferré-Bigorra et al., 2022; Scalas et al., 2022; Miller et al., 2021). Secondly, these twins are meant to establish a flexible and adaptive digital model, continuously learning and evolving in sync with the dynamic nature of the actual city (Alva et al., 2022; Lehtola et al., 2022). Finally, they serve as predictive models, offering the capability to anticipate and simulate future urban scenarios (Lei et al., 2023).

Within this context, our research gathers the potential of urban data, such as 3D geoinformation, and technologies, such as UDT, to unpack the complexities of outdoor thermal comfort in urban areas. It builds upon recent trends on integrating novel types of dynamic data into UDTs to augment their value and unlock new use cases (Ramani et al., 2023), and giving prominence to data such as street view imagery (SVI), which can be considered as a form of volumetric mapping, contributing to the creation of detailed 3D representations of urban spaces (Biljecki and Ito, 2021), but not much in focus of UDTs hitherto. The UDT, acting as a virtual counterpart, not only replicates the physical attributes but also simulates thermal variations in response to environmental factors, providing a nuanced understanding of microclimatic influences (Ferré-Bigorra et al., 2022; Tong and Chao, 2023).

In this work, we present a novel integration of smartwatch data, 3D spatial technologies, and other urban information leading to a UDT that may enable us to transcend traditional boundaries in urban studies and city management. Such a digital twin, with its dynamic nature, may facilitate the observation of how thermal conditions evolve over time, allowing for scenario testing and predictive modeling. Such a direction may support urban climatology, enhance walkability in cities, and set the stage for a comprehensive investigation into how the three-dimensional urban landscape influences the well-being and experiences of its inhabitants.

1.2 Outdoor Thermal Comfort

Outdoor thermal comfort is pivotal in urban studies, bearing substantial implications for human health, well-being, and productivity, as well as the sustainability of urban environments (Givoni et al., 2003; Nikolopoulou et al., 2001). It influences people's thermal sensations, impacting physiological responses, mood, and behavior (Wei et al., 2013a,b; Lai et al., 2020). Extreme conditions, like heat waves or cold spells,

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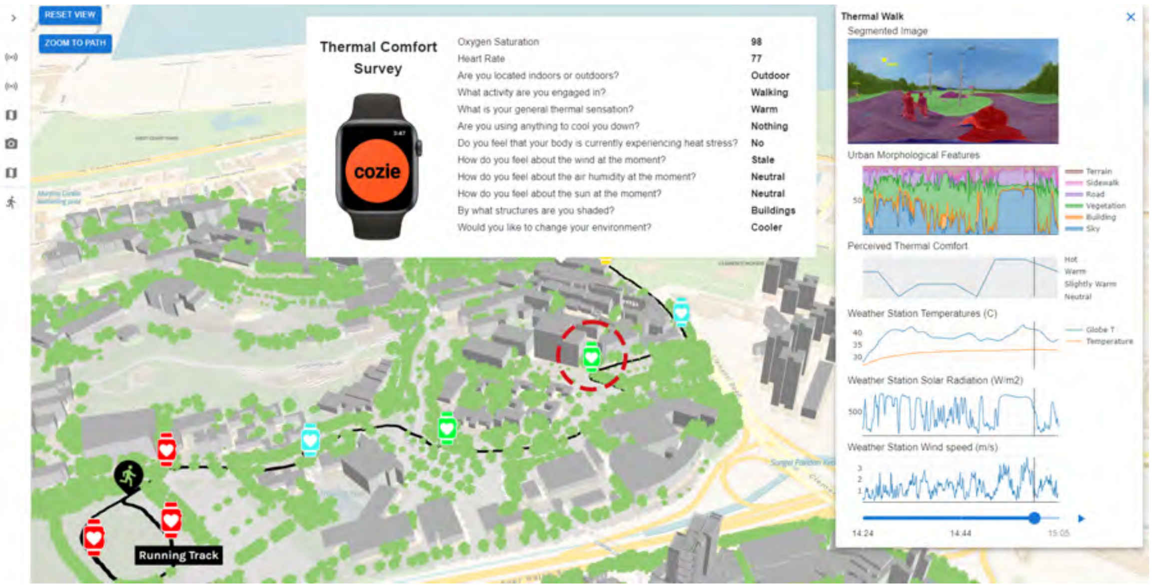


Thermal Comfort Survey

Oxygen Saturation	98
Heart Rate	77
Are you located indoors or outdoors?	Outdoor
What activity are you engaged in?	Walking
What is your general thermal sensation?	Warm
Are you using anything to cool you down?	Nothing
Do you feel that your body is currently experiencing heat stress?	No
How do you feel about the wind at the moment?	Stale
How do you feel about the air humidity at the moment?	Neutral
How do you feel about the sun at the moment?	Neutral
By what structures are you shaded?	Buildings
Would you like to change your environment?	Cooler

Figure 1. Thermal Walk visualization interface. This instance of an urban digital twin enables understanding the multi-faceted dynamic data collected in relation to understanding the outdoor thermal comfort and the influence of the surrounding 3D environment.

pose health risks, especially for vulnerable populations (Nikolopoulou and Lykoudis, 2006; Banerjee et al., 2022).

Recent literature underscores the significance of outdoor thermal comfort. Studies employing field measurements and simulations investigate the impact of microclimate conditions on thermal comfort (Cheng et al., 2012; Tan et al., 2013; He et al., 2015). They reveal the substantial influence of urban microclimates on thermal comfort, emphasizing the positive role of green spaces and water bodies. Furthermore, the research explores the correlation between outdoor thermal comfort and physical activity in urban parks, revealing that thermal comfort fosters increased engagement in physical activities (Chen and Ng, 2012; Ng et al., 2012).

Outdoor thermal comfort in urban areas became a priority of many local governments and research groups around the world, as neglecting it poses serious risks, including health issues during extreme conditions (Lau et al., 2019; Reem et al., 2022). Suboptimal thermal conditions also lead to reduced productivity and well-being, with economic and social implications. Ignoring outdoor thermal comfort in urban development exacerbates the urban heat island effect, increasing energy consumption and greenhouse gas emissions, negatively impacting the environment (Banerjee et al., 2022).

Ensuring healthy, sustainable, and livable urban environments necessitates prioritizing outdoor thermal comfort in urban studies and planning. In Singapore — our study area — a highly urbanized city-state, the urban heat island effect significantly affects the pedestrian environment (Wei et al., 2013a; Sikram et al., 2020; Heng and Chow, 2019). As the urban form and design of streets play a monumental role in driving comfort, studies, such as one on the urban geometry in Singapore's central business district, emphasize the importance of factors such as street orientation and building characteristics in improving pedestrian thermal comfort (Banerjee et al., 2022).

To pursue a more comprehensive analysis of into outdoor thermal comfort domain, our team has chosen to focus on thermal walks, a method that involves complex subjective and objective data collection during the activity of walking. This approach captures a diverse range of data, providing a comprehensive understanding of how individuals experience thermal conditions in real-time (Dzyuban et al., 2022; Chàfer et al., 2022; Kim et al., 2023; Dyzuban, 2024).

Pioneer studies have investigated new techniques to evaluate thermal comfort and understanding how environmental factors influencing pedestrians through mobile measurements or stop-and-go techniques (Chokhachian et al., 2018; Peng et al., 2022). These studies have shown significant variations in meteorological conditions and how individuals perceive temperature while walking in urban areas. Additional studies have centered the evaluation around pedestrian thermal comfort in different urban environments in Singapore indicate that covered pedestrian walkways offer the most comfortable conditions, followed by green spaces and open-air walkways (Wei et al., 2013a, 2015). Such findings underscore the importance of comprehending how urban interventions and urban elements, such as covered walkways and greenery, contribute to the improvement pedestrian thermal comfort. Given their capacity in capturing, simulating, and optimizing the built environment, UDT are valuable to support such studies and plan urban interventions.

1.3 Crowdsourced data and wearables in urban comfort studies

Recent years have witnessed a growing interest in using crowdsourced data to study urban spaces (Huang et al., 2024). Crowdsourced data, in the context of geospatial studies, often refers to user-generated geographic content. Although researching human comfort studies largely relies on the data collected through professional equipment, crowdsourcing such data through mobile devices and applications (e.g., Fitbit, Apple Watch) is gaining its prevalence (Tartarini et al., 2023).

The advantages of utilizing wearables for data collection during thermal walks are significant in enhancing the study of outdoor thermal comfort (Liu et al., 2023). Their continuous monitoring ability is a key strength, as wearables can collect data throughout an entire walk, offering a detailed and comprehensive dataset that surpasses intermittent or one-time measurements (Lei et al., 2024). Real-time feedback is another notable benefit, empowering wearers to make immediate adjustments to their behavior or clothing in response to changing thermal conditions. Considering their dynamic and real-time properties, the integration of such data in UDTs may strengthen their interface with the real world and deliver the promise of a ‘true’ digital twin.

Wearable technology contributes to data objectivity by collecting precise information on environmental and biometric factors, minimizing potential bias or subjectivity in the data collection process. The capability to collect data from a large number of participants simultaneously is a noteworthy advantage, facilitating more robust statistical analyses and generalizable findings. Importantly, wearables provide a non-intrusive method of data collection, eliminating the need for participants to carry additional equipment or disrupt their natural behavior, thus ensuring convenience and minimal interference.

Hence, this method for data collection during structured walks as a controlled study with participants represents a sophisticated and advanced approach to studying outdoor thermal comfort. This methodology not only ensures greater precision, accuracy, and richness of data but also offers a streamlined and user-friendly experience for participants, marking a significant improvement over traditional data collection methods.

Its primary objective is to explore the integration and utilization of smart wearables, SVI segmentation techniques, and weather sensors in a UDT. The investigation dives into the methodology, examining the efficacy of the implemented data and the impact of urban morphology on thermal perception and physiological responses, thus contributing valuable insights in future studies to the fields of climatology and human-centric design. Further contributions include the data integration and use case aspects, considering that the concoction of such data has not been the subject of UDT literature so far, which may contribute to unlocking a new use case for using UDTs.

Central to this investigation are two key research questions, presenting an initial methodology for a comprehensive understanding of the complex relationship between environmental factors and human experiences:

- How can a methodological framework be developed for the quantification and evaluation of comprehensive thermal comfort factors, facilitating their seamless integration into an urban digital twin?
- What potential use cases can be identified for the integrated data and the implemented UDT?

1.4 Research Aim and Objective

This research aims to establish a geospatial (UDT) infrastructure supporting the goal of understanding the impact of outdoor thermal comfort on walkability in urban tropics. Pursuing this objective, we implement a complete and novel workflow from conceptualization and data acquisition to data integration and visualization in a digital twin interface (Figure 1), which we introduce and elaborate on in the continuation of the paper.

2. Thermal Walk

The proposed research is centered around exploring perceptual variations in thermo-spatial conditions and comfort states encountered by pedestrians navigating interconnected spaces. The study employs a structured approach involving thermal walks along selected pedestrian routes, introducing variations in urban settings and route elevations. It is conducted in a university campus, with routes passing through different settings, such as roads, sheltered walkways, tree-lined pavements, and open spaces.

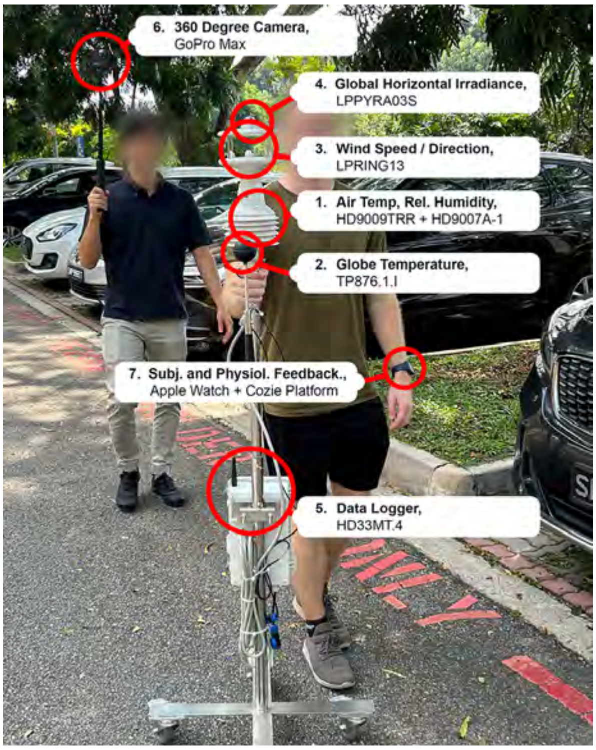


Figure 2. Documentation of the the experimental setup of the Thermal Walk with sensor descriptions.

During these thermal walks, the research conducts microclimatic monitoring and field surveys to assess thermal perceptions using wearable technology. The emphasis is placed on understanding the nuanced variations in comfort states throughout the journey. The primary focus of the research is on comprehending the overall experience of the thermal walk and its influence on the dynamic thermal perception of pedestrians, supported with 3D geoinformation and other urban data.

The data collection methodology during the structured thermal walk involves harnessing the capabilities of the Apple Watch to gather diverse sets of information crucial for analyzing outdoor thermal comfort conditions. This comprehensive approach encompasses environmental data, capturing parameters like temperature, humidity, and barometric pressure to analyze microclimatic conditions. Simultaneously, the Apple Watch tracks biometric responses, including heart rate and respiratory rate, providing insights into how the human body reacts to thermal variations.

Furthermore, the study investigates whether interconnected spaces with high-density lead to differentiated thermal pleasantness between streets and squares. Additionally, the research explores whether movement and complexity in urban morphology along a sequence contribute to an enriched diversity in thermal sensation.

The insights gained from this research have the potential to inform the development of multisensory-centered urbanism. In this context, the study suggests that prioritizing the experience of the thermal environment can play a pivotal role in perception-driven and healthier urban design practices.

2.1 Microclimate data colletion with mobile weather station

Throughout the thermal walk, a mobile weather station is deployed to conduct microclimate measurements, logging temperature, wind speed and direction, relative humidity, and radiation, using various sensors as depicted in Figure 2. The mobile weather station was pushed manually and maintained a continuous slow-paced movement, with interruptions for each Cozie smartwatch micro-survey.

The detailed sensor arrangement within the mobile weather station is provided in Table 1, offering insights into sensor types and corresponding accuracies. The Data Logger HD33MT.4 was utilized for configuring and logging environmental data, employing a 10-second measurement interval and a 1-minute logging interval for the data collection.

To ensure accurate measurements of the ambient conditions, the mobile weather station was set outside in the environment 10 minutes before the beginning of the climate walk to allow for sufficient acclimatization.

2.2 SVI data collection and segmentation

SVI data were captured with panoramic video recordings using a GoPro Max. Subsequently, panoramic frames were extracted at five-second intervals for SVI segmentation. The leveling of each frame was achieved using the GoPro Player software (version 2.1.29.0) and its Horizon Leveling function.

The collected SVI data underwent segmentation to identify and quantify the common set of urban morphological variables using computer vision techniques (Biljecki et al., 2023). Pixel ratio values were obtained for key variables such as sky, buildings, greenery, sidewalk, terrain, and road ratio.

Quantifying urban morphology, particularly through SVI segmentation, is essential for understanding the intricate relationships between microclimate and the built environment at the pedestrian level. SVI segmentation allows for the estimation of topical indicators, offering insights into the physical characteristics of the built environment, including building arrangement and green space distribution. By integrating these variables, it becomes possible to evaluate how solar exposure, building obstruction, surface permeability, and the extent of green spaces influence local microclimate conditions, particularly ambient temperature experienced by pedestrians.

To conduct semantic segmentation of SVI, we utilized the Mask2Former model pre-trained on the CityScapes dataset with 84.5% mIoU and 19 categories (Cheng et al., 2022). Segmented SVI images were split and transformed into fish-eye views for accurate assessment of urban morphological metrics like buildings, greenery, terrain, sidewalks, and roads. The equisolid transformation in the upper half ensures a precise depiction of proportions, especially vital for metrics like buildings and trees, focusing on the dedicated view proportion of specific features.

We utilized an orthographic transformation to convert panorama images into a fisheye view, preserving angles and ensuring an accurate representation of the visible sky in urban environments. This approach is particularly valuable for precise Sky View Factor (SVF) calculations, emphasizing zenith angles for reliable sky visibility depiction, crucial in urban canyons and areas with tall structures.

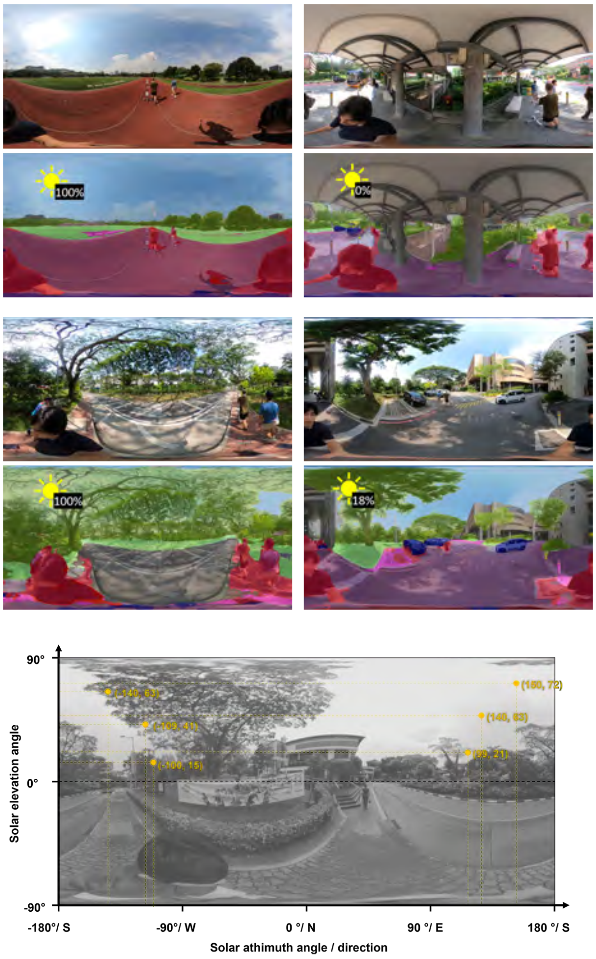


Figure 3. *(Top)* SVI segmentation from four locations, with calculated solar position and exposure level. *(Bottom)* Mapping solar positions on panoramic imagery.

2.3 Vizualising solar position

Understanding the impact of direct solar radiation is essential in assessing urban thermal comfort. We have, therefore, developed a method to visualize solar positions in segmented panoramic imagery. This technique is crucial for determining exposure to direct solar radiation, which can be influenced by obstructions such as tree crowns or buildings.

The method involves calculating the solar position, which is defined by two parameters: solar elevation and solar azimuth angle. These calculations are performed using ’pvlib’ (Holmgren et al., 2018), a Python module designed primarily for estimating solar radiation gain on photovoltaic (PV) panels. In ‘pvlib,’ the solar position is determined based on geographical coordinates (latitude and longitude), date, and time (Reda and Andreas, 2004).

After calculating the solar position, we map it onto a panoramic image. This mapping aligns the calculated solar position with the corresponding pixel coordinates in the image. This approach is feasible due to the use of equirectangular projection

ID	Data	Unit	Sensor type	Model	Accuracy
1	Air Temperature, Relative Humidity	°C	Combined temperature and humidity probe, with solar radiation shield	HD9009TRR and HD9007A-1	± 0.2 °C, ±2 %
2	Globe Temperature	°C	Globe thermometer 50 mm	TP876.1.I	±0.1 °C
3	Wind speed, direction	m/s	Omni-directional hotwire probe	HD4V3TS2	±0.2 m/s + 3 %
4	Global Horizontal Irradiance	W/m^2	Class C pyranometer with MODBUS-RTU output	LPPYRA03S	±20 W/m^2, ±2 %

Table 1. Overview of the mobile weather station sensors with a measurement interval of 10 seconds and a logging interval of 1 minute.

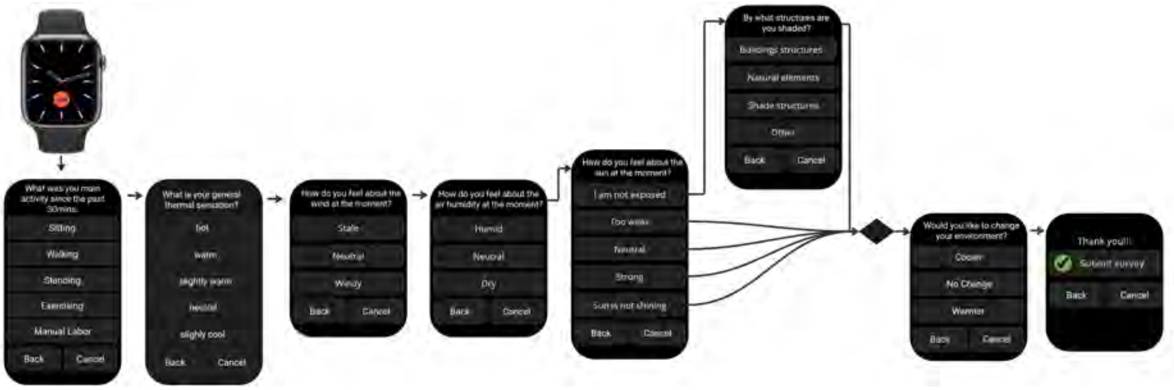


Figure 4. The questions workflow that is displayed to the user via the Cozie platform in Apple Watch.

in creating our panoramic imagery. In this projection, the horizontal coordinate corresponds to the azimuth angle, and the vertical coordinate corresponds to the elevation angle. Samples of both SVI output and calculated solar position are shown in Figure 3.

By integrating this method into our urban analytics framework, we believe we can more accurately assess and visualize the impact of solar radiation on urban thermal comfort, leading to better-informed urban planning and design strategies.

2.4 Data collection with smart wearables

Cozie is a platform to collect subjective and physiological human comfort data (Tartarini et al., 2023). Location data, obtained through the Cozie platform and its tracking capabilities during and in between micro-surveys, supplements the mapping of the route taken and analysis of thermal condition variations across different segments of the walk. The micro surveys capture the subjective feedback as well as other environmental information on a survey basis in real-time along the route (Liu et al., 2023). An overview of the survey workflow is described in Figure 4. The question workflow is response-dependent. Additionally, physiological data consisting of Heart Rate, Blood Pressure, Blood Oxygen Saturation, and activity data encompassing activity data, like walking speed and step count, are logged. For this study, the Cozie V3 for Apple with Apples Watches was utilized to collect feedback and additional aforementioned data.

3. Thermal walk data management and visualisation through a digital twin

Following the collection of data, a web-based digital twin interface was created to visualize the results from the thermal walk alongside the 3D context of the campus, including terrain, buildings, and trees. It aims to provide an interactive platform that allows one to navigate along the path taken and compare the recorded measurements and responses with both the segmented images and the overall 3D environment.

The interface was created using deck.gl, a WebGL and React-based framework that comes with a rich layer catalog for visualization of different datasets (Wang, 2019).

3.1 Data processing for visualization

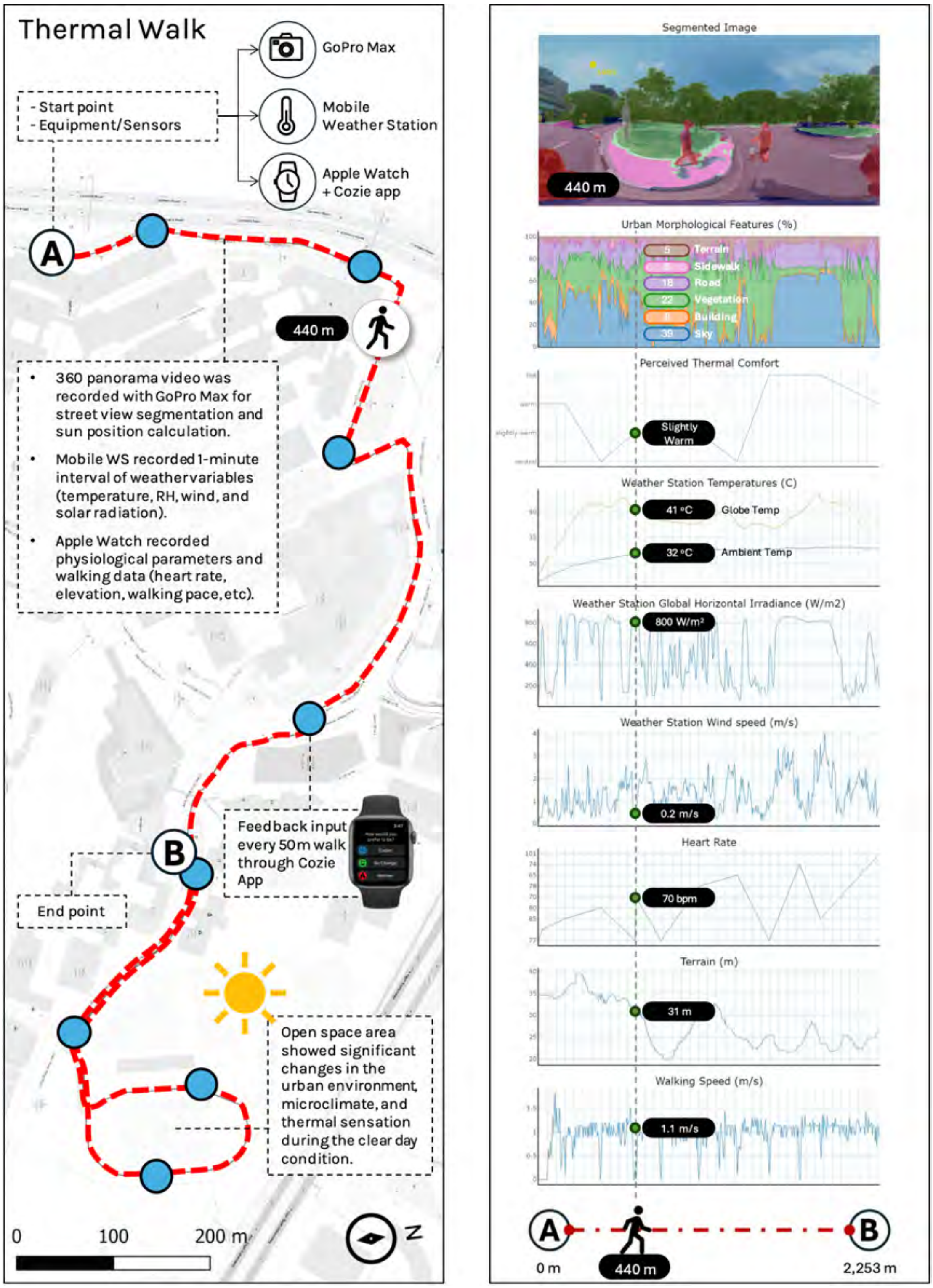
The processed data collected from the GoPro, mobile weather station, and smartwatch were synchronized to share timestamps and locations, using each frame exported by the GoPro for each point along the walk. The data was combined and exported as two JSON files.

The first file is used for the visualization of the thermal walk path in deck.gl. This file contains the location of each point in the form of latitude, longitude, and altitude values, as well as recorded smart watch measurements and responses at corresponding points. The file is loaded and visualized using PathLayer and IconLayer.

The second file is used for the visualization of plots summarizing the image segmentation results and mobile weather station measurements. This file contains selected image segmentation results that were of interest (such as sky, building, and vegetation), measurements (such as temperature, global horizontal irradiance, and wind speed), and smartwatch readings (such as heart rate and thermal perception). The data is formatted and displayed using react-plotly.js (Inc., 2015).

3.2 Visualization results

The resulting interface integrating the processed multi-source data is shown in Figure 1. Adjusting the slider moves a marker along the path and displays the corresponding segmented image. Clicking on each smart watch icon displays a popup with the smartwatch measurements and responses recorded at that location.



- 360 panorama video was recorded with GoPro Max for street view segmentation and sun position calculation.
- Mobile WS recorded 1-minute interval of weather variables (temperature, RH, wind, and solar radiation).
- Apple Watch recorded physiological parameters and walking data (heart rate, elevation, walking pace, etc).

Feedback input every 50 m walk through Cozie App

Open space area showed significant changes in the urban environment, microclimate, and thermal sensation during the clear day condition.

Figure 5. Thermal walk data collection and visualisation.

Navigating along the path in this manner, one can visually identify potential trends or points of interest. For example, the running track and sports field is an open area with segmented images that contain a high percentage of sky and a low percentage of vegetation and buildings that provide shade. This phenomenon correlates with high temperature measurements and the perception of the area being hot despite higher wind speeds. A detailed view of the data is shown in Figure 5.

4. Discussion

The thermal walk presents an examination of environmental dynamics and subjective comfort. Unlike conventional pedestrian longitudinal studies, this study is affected by pushing a mobile weather station, which amplifies bodily strain, resulting in heightened discomfort, but enables the assessment of additional environmental parameters close to the subject. The environmental assessment could be improved by using a backpackmounted system instead of a trolley to remove the resistance of pushing the mobile weather station and ease the process of doing and capturing during walking.

Additionally, broadening physiological measurements beyond conventional parameters could be relevant. Integrating metrics such as metabolic rate, core body temperature, skin temperature, and sweat rate offers a more comprehensive perspective on the physiological strain on the thermoregulation system during the thermal walk. Future research should refrain from the limited diversity of subjective responses. To enhance the reliability and validity of subjective responses on thermal perception, a more diverse participant group should be considered, even if they cannot be engaged simultaneously.

This study focuses on developing a proof of concept of infrastructure and methodology that would support such studies, thus the data for the thermal walk contributed and integrated into the UDT is not representative. In order to analyze and formulate assumptions from the subjective and physiological responses in correlation with the built environment, a greater amount and diverse response data are needed. The thermal walk should also be done multiple times during the day and during different seasons to depict a full picture, in this case, of the microclimate of the tropics. Future work will focus on more thermal walks and their impacts, as well as how to integrate and present a greater amount of data into the UDT. In addition to providing a way to visualize and identify trends along thermal walk trips, future developments could support the classification of paths by similar urban morphological feature distributions and highlighting commonly used paths or hot spots.

The novel integration of data turned out to be relatively straightforward and ended up being represented in a clear manner in the interface (Figure 1). However, further work is required to make such integration more robust. For example, the development of a mechanism to integrate such data in a 3D standard such as CityJSON (Ledoux et al., 2019) is desirable.

Nevertheless, this methodology does not differ in general for different climates. Only the Cozie question workflow needs to be adapted regarding the thermal perception. In this case, questions regarding heat stress due to the intense temperatures in the tropics were additionally deployed. A different climate also influences when and where the thermal walk should be deployed.

Finally, the current 3D model used is not fully representative of the actual environment captured by the SVI. Some important features like shrubs and sheltered walkways are not captured. We are in the process of creating a more accurate and updated 3D model of the study area and will work on integrating it in future development.

5. Conclusion

In this work, we developed a proof of concept of an urban digital twin that integrates emerging forms of urban data (e.g., wearables, street view imagery) to sense outdoor thermal comfort and influence of the built environment and support the planning and management of interventions that would improve walkability. Nevertheless, this paper only featured one participant in order to present and evaluate the methodology and approach focusing on the integration into UDTs. Future studies, should investigate greater number and variety of participants to describe and analyze the influences of the outdoor environment on human physiology. The proposed framework offers a comprehensive understanding of how irregular urban forms influence thermal diversity at the street level. It provides valuable insights into urban morphologies, solar exposure correlations, and the experiential aspects of ambient temperature. However, additional data is crucial for a thorough evaluation of these impacts. Future data analysis can further support the assessment and demonstration of the effects of temporal environmental adjustments in the built environment, including changes in vegetation, urban layout modifications, and responses to climate change. Subsequent research efforts should focus on refining data assessment methodologies and presenting larger datasets, enabling the development of machine learning models for predicting outdoor comfort.

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References

Alva, P., Biljecki, F., Stouffs, R., 2022. Use Cases for District-scale Urban Digital Twins. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, XLVIII-4/W4-2022, 5-12. ISPRS-Archives.

Banerjee, S., Ching, G. N. Y., Yik, S. K., Dzyuban, Y., Crank, P. J., Pek, R. X. Y., Chow, W. T., 2022. Analysing impacts of urban morphological variables and density on outdoor microclimate for tropical cities: A review and a framework proposal for future research directions. *Building and Environment*, 225, 109646.

Biljecki, F., Ito, K., 2021. Street view imagery in urban analytics and GIS: A review. *Landscape and Urban Planning*, 215, 104217.

Biljecki, F., Zhao, T., Liang, X., Hou, Y., 2023. Sensitivity of measuring the urban form and greenery using street-level imagery: A comparative study of approaches and visual perspectives. *International Journal of Applied Earth Observation and Geoinformation*, 122, 103385.

Chen, L., Ng, E., 2012. Outdoor thermal comfort and outdoor activities: A review of research in the past decade. *Cities*, 29(2), 118-125.

Cheng, B., Misra, I., Schwing, A. G., Kirillov, A., Girdhar, R., 2022. Masked-attention mask transformer for universal image segmentation.

Cheng, V., Ng, E., Chan, C., Givoni, B., 2012. Outdoor thermal comfort study in a sub-tropical climate: a longitudinal study based in Hong Kong. *International Journal of Biometeorology*, 56(1), 43-56.

Chokhachian, A., Ka-Lun Lau, K., Perini, K., Auer, T., 2018. Sensing transient outdoor comfort: A georeferenced method to monitor and map microclimate. 20, 94–104.

Chàfer, M., Tan, C. L., Cureau, R. J., Hien, W. N., Pisello, A. L., Cabeza, L. F., 2022. Mobile measurements of microclimatic variables through the central area of Singapore: An analysis from the pedestrian perspective. *Sustainable Cities and Society*, 83, 103986.

Dyzuban, Y., 2024. Thermal walk for outdoor thermal comfort evaluation of urban spaces in an Asian city.

Dzyuban, Y., Hondula, D. M., Vanos, J. K., Middel, A., Coseo, P. J., Kuras, E. R., Redman, C. L., 2022. Evidence of alliesthesia during a neighborhood thermal walk in a hot and dry city. *Science of The Total Environment*, 834, 155294.

Ferré-Bigorra, J., Casals, M., Gangolells, M., 2022. The adoption of urban digital twins. *Cities*, 131, 103905.

Givoni, B., Mikiko, N., Hadas, S., Oded, P., Yaron, Y., Noa, F., Stefan, B., 2003. Outdoor comfort research issues. *Energy and Buildings*, 35(1), 77-86.

He, X., Miao, S., Shen, S., Li, J., Zhang, B., Zhang, Z., Chen, X., 2015. Influence of sky view factor on outdoor thermal environment and physiological equivalent temperature. *International Journal of Biometeorology*, 59(3), 285-297.

Heng, S. L., Chow, W. T. L., 2019. How ‘hot’ is too hot? Evaluating acceptable outdoor thermal comfort ranges in an equatorial urban park. *International Journal of Biometeorology*, 63(6), 801-816.

Holmgren, W. F., Hansen, C. W., Mikofski, M. A., 2018. pvlib python: a python package for modeling solar energy systems. *Journal of Open Source Software*, 3(29), 884. https://doi.org/10.21105/joss.00884.

Huang, X., Wang, S., Yang, D., Hu, T., Chen, M., Zhang, M., Zhang, G., Biljecki, F., Lu, T., Zou, L., Wu, C. Y. H., Park, Y. M., Li, X., Liu, Y., Fan, H., Mitchell, J., Li, Z., Hohl, A., 2024. Crowdsourcing Geospatial Data for Earth and Human Observations: A Review. *Journal of Remote Sensing*, 4(0105).

Inc., P. T., 2015. Collaborative data science.

Kim, Y., Jang, S., Kim, K. B., 2023. Impact of urban microclimate on walking volume by street type and heat-vulnerable age groups: Seoul’s IoT sensor big data. *Urban Climate*, 51, 101658.

Lai, D., Lian, Z., Liu, W., Guo, C., Liu, W., Liu, K., Chen, Q., 2020. A comprehensive review of thermal comfort studies in urban open spaces. 742, 140092.

Lau, S. S. Y., Zhang, J., Tao, Y., 2019. A comparative study of thermal comfort in learning spaces using three different ventilation strategies on a tropical university campus. *Building and Environment*, 148, 579-599.

Ledoux, H., Arroyo Ohori, K., Kumar, K., Dukai, B., Labetski, A., Vitalis, S., 2019. CityJSON: a compact and easy-to-use encoding of the CityGML data model. *Open Geospatial Data, Software and Standards*, 4(4).

Lehtola, V. V., Koeva, M., Elberink, S. O., Raposo, P., Virtanen, J.-P., Vahdatikhaki, F., Borsci, S., 2022. Digital twin of a city: Review of technology serving city needs. *International Journal of Applied Earth Observation and Geoinformation*, 114, 102915.

Lei, B., Janssen, P., Stoter, J., Biljecki, F., 2023. Challenges of urban digital twins: A systematic review and a Delphi expert survey. *Automation in Construction*, 147, 104716.

Lei, B., Su, Y., Biljecki, F., 2024. Humans as sensors in urban digital twins. *Recent Advances in 3D Geoinformation Science*, Springer Nature Switzerland, 693–706.

Liu, P., Zhao, T., Luo, J., Lei, B., Frei, M., Miller, C., Biljecki, F., 2023. Towards Human-centric Digital Twins: Leveraging Computer Vision and Graph Models to Predict Outdoor Comfort. *Sustainable Cities and Society*, 93, 104480.

Miller, C., Abdelrahman, M., Chong, A., Biljecki, F., Quintana, M., Frei, M., Chew, M., Wong, D., 2021. The Internet-of-Buildings (IoB) — Digital twin convergence of wearable and IoT data with GIS/BIM. *Journal of Physics: Conference Series*, 2042(1), 012041.

Ng, E., Chen, L., Wang, Y., Yuan, C., 2012. A study on the cooling effects of greening in a high-density city: An experience from Hong Kong. *Building and Environment*, 47, 256–271.

Nikolopoulou, M., Baker, N., Steemers, K., 2001. Thermal comfort in outdoor urban spaces: understanding the human parameter. *Urban Environment*, 70(3), 227-235.

Nikolopoulou, M., Lykoudis, S., 2006. Thermal comfort in outdoor urban spaces: Analysis across different European countries. *Building and Environment*, 41(11), 1455-1470.

Peng, Z., Bardhan, R., Ellard, C., Steemers, K., 2022. Urban climate walk: A stop-and-go assessment of the dynamic thermal sensation and perception in two waterfront districts in Rome, Italy. *Building and Environment*, 221, 109267.

Ramani, V., Ignatius, M., Lim, J., Biljecki, F., Miller, C., 2023. A Dynamic Urban Digital Twin Integrating Longitudinal Thermal Imagery for Microclimate Studies. *Proceedings of the 10th ACM International Conference on Systems for Energy-Efficient Buildings, Cities, and Transportation*, 421–428.

Reda, I., Andreas, A., 2004. Solar position algorithm for solar radiation applications. *Solar Energy*, 76(5), 577–589.

Reem, Ashraf, E., Naglaa, M., Osama, Sara, E., 2022. The impact of urban geometry on outdoor thermal comfort in a hot-humid climate. *Building and Environment*, 225, 109632.

Scalas, A., Cabiddu, D., Mortara, M., Spagnuolo, M., 2022. Potential of the Geometric Layer in Urban Digital Twins. *ISPRS International Journal of Geo-Information*, 11(6), 343.

Sikram, T., Ichinose, M., Sasaki, R., 2020. Assessment of Thermal Comfort and Building-Related Symptoms in Air-Conditioned Offices in Tropical Regions: A Case Study in Singapore and Thailand. *Frontiers in Built Environment*, 6.

Tan, C. L., Wong, N. H., Jusuf, S. K., 2013. Outdoor mean radiant temperature estimation in the tropical urban environment. *Building and Environment*, 64, 118-129.

Tartarini, F., Frei, M., Schiavon, S., Chua, Y. X., Miller, C., 2023. Cozie Apple: An iOS mobile and smartwatch application for environmental quality satisfaction and physiological data collection. *Journal of Physics: Conference Series*, 2600(14), 142003.

Tong, L., Chao, F., 2023. *A Digital Twin Framework to Simulate Urban Microclimates*. American Society of Civil Engineers, Arlington, Virginia, 617–622.

Wang, Y., 2019. Deck. gl: Large-scale web-based visual analytics made easy. *arXiv preprint arXiv:1910.08865*.

Wei, Y., Wong, N. H., Jusuf, S. K., 2013a. Thermal comfort in outdoor urban spaces in Singapore. *Building and Environment*, 59, 426-435.

Wei, Y., Wong, N. H., Lin, Y., 2015. Thermal Comfort in High-rise Urban Environments in Singapore. *Procedia Engineering*, 121, 2125-2131.

Wei, Y., Wong, N. H., Zhang, G., 2013b. A comparative analysis of human thermal conditions in outdoor urban spaces in the summer season in Singapore and Changsha, China. *International Journal of Biometeorology*, 57(6), 895-907.