

# UNFOLDING THE USER EXPERIENCE: A COMPREHENSIVE USER EXPERIENCE FRAMEWORK FOR FOLDABLE SMARTPHONES

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This study presents a comprehensive framework for understanding User Experience (UX) in foldable smartphones, a rapidly emerging mobile technology category. Through product research, user studies, and expert evaluations, this research identifies three core elements: the hinge, the user, and the folding-state interface. The framework emphasizes the hinge's crucial role in maintaining screen continuity, enhancing portability, and ensuring user comfort during folding operations. Ergonomic compatibility and psychological acceptability are identified as essential user factors, while state consistency, intuitive compatibility, proper feedback, and exclusive features constitute vital interface elements. An exploratory case study examining the impact of hand size on UX revealed significant differences in pressure application and fatigue levels between users with different hand sizes, highlighting the importance of ergonomic considerations in design. This framework provides a foundation for future development in foldable smartphones, aiming to improve product attractiveness by systematically addressing specific user requirements and experiences.

**Keywords:** Foldable Smartphones; User Experience; Human-Computer Interaction; Hinge.

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## 1. INTRODUCTION

Foldable smartphones represent the newest category of mobile computing devices. These devices combine tablet productivity with smartphone portability (Verge, 2020). Growing demand for portable devices with large screens drives foldable smartphone development, making them a leading force in mobile technology.

Based on their folding method, foldable smartphones fall into three categories: inward folding, outward folding, and vertical folding (Huang, 2021). Inward foldable smartphones possess distinct attributes, namely the presence of dual screens. The inner screen has larger dimensions to facilitate usage when the phone is unfolded, while the outer screen is smaller, resembling a conventional phone, enabling usage when the device is closed. This folding technique preserves the inner screen's integrity, reducing folding damage and minimizing crease formation. However, this increases the phone's weight and thickness, creating challenges for manufacturers in component stacking and hinge design. Outward foldable smartphones are characterized by the presence of a solitary, expansive display that envelops the entirety of the device when it is in a closed state. The folding technique offers a notable benefit in managing the phone's weight and thickness. However, due to the constant exposure to the screen, there exists a potential for the occurrence of screen scratches. Unlike the previous two options, vertical foldable smartphones specifically cater to women or the fashion industry. When in the unfolded state, they possess a size comparable to that of standard phones, and when folded, they reduce to nearly half of their original size. The primary benefit of vertical foldable smartphones is their portability. However, the absence of a fully operational screen when closed creates a trade-off in terms of convenience for accessing information. In contemporary times, prominent smartphone manufacturers, including SAMSUNG, HUAWEI, vivo, OPPO, and various others, have unveiled vertical foldable smartphones that incorporate a compact screen adjacent to the camera module, catering to the demands of lightweight browsing and entertainment.

Numerous factors influence the user experience (UX) of foldable smartphones; however, there is a lack of comprehensive research by the academic community on these factors. The objective of this study is to develop a UX framework for foldable smartphones. This study defines the UX concept for foldable smartphones and proposes the essential elements of a UX framework for foldable smartphones, focusing on the hinge, through thorough product research, use case studies, and evaluations. This study demonstrates the impact of the proposed elements on the UX of foldable smartphones, as evidenced by a literature review. In order to ascertain the validity of the proposed framework, a simple case study was designed and conducted. By utilizing the proposed framework for UX in foldable smartphones, service providers can

systematically collect data and analyze the manner in which consumers engage with foldable smartphone products. This framework facilitates a more profound understanding of user requirements, acting as an important component to improve the attractiveness and market standing of their products or services.

This study addresses three specific research questions: (1) What are the core elements that constitute the user experience framework for foldable smartphones? (2) How do these elements interact to influence user satisfaction and usability in foldable smartphone interactions? (3) How can this framework be validated and applied to improve foldable smartphone design? By answering these questions, this research aims to establish a systematic approach for understanding and enhancing UX in the rapidly evolving foldable smartphone market.

The significance of this research is both theoretical and practical. Theoretically, this study addresses a critical gap in UX research by developing the first comprehensive framework specifically designed for foldable smartphones, moving beyond fragmented studies of individual features. The framework established the hinge as a central UX determinant, contributing to human-computer interaction theory for emerging form factors. Practically, this research provides manufacturers with systematic design guidance to improve user satisfaction and product adoption. With the foldable smartphone market continuing to grow, understanding UX factors becomes crucial for competitive advantage and user acceptance of this emerging technology.

## 2. BACKGROUND AND RESEARCH METHOD

### 2.1. User Experiences (UX)

ISO defines UX as "a person's perceptions and responses resulting from the use and/or anticipated use of a product, system or service" (Mirnig *et al.*, 2015; Olsson *et al.*, 2013), meaning UX encompasses all aspects of the user's interaction with the product, system, or service (Alben, 1996; Law *et al.*, 2009), and can serve across the entire product lifecycle, playing a role in design, usage, and post-use evaluation, with the aim of enhancing user satisfaction and preferences (Anitha and Prabhu, 2012; Deng *et al.*, 2010).

Usability is a frequently examined concept in conjunction with UX. Usability, as defined by ISO, refers to "the capability of the software product to be understood, learned, used and attractive to the user, when used under specified conditions" (Abran *et al.*, 2003). The prevailing consensus within the academic community is that usability is a component of UX. Usability primarily focuses on evaluating the objective usability attributes of a product, whereas UX includes a broader concept that takes into account subjective factors such as the user, the environment, and other relevant conditions (Lin *et al.*, 2016; Sauer *et al.*, 2020; Rusu *et al.*, 2015).

UX can be evaluated and categorized using different methods. UX design and evaluation, when viewed through the lens of a man-machine system, commonly encompass three key dimensions: the human, the machine, and the environment (Berry and Broadbent, 1987; Kontogiannis, 1999). An alternative method of categorization, which prioritizes the user, delineates UX by considering three dimensions that constitute the comprehensive notion of general UX: usability, affect, and sociability (Jang and Han, 2022; Hassenzahl *et al.*, 2010). Various products or services possess distinct interpretations of UX. Davis and Wong (2007) provide a definition of the UX of eLearning as the educational experience that students have while using eLearning services, which includes the system and environment. Similarly, Wang (2020) demonstrates how user preferences and performance ratings can be incorporated into product design and recommendation systems for multi-functional tablets, highlighting the importance of user-centered approaches for emerging technologies. The core elements that comprise the UX of eLearning are identified as system use, technology acceptance, and the flow experience. In the realm of blockchain, the focus extends beyond general UX to encompass technological UX, which is a concept to describe the UX only the service or product can provide, includes social value, economic value, and trust (Jang and Han, 2022). This shows that the definition and focus of UX can be tailored and improved based on the research topic and objectives.

### 2.2. Interacting with foldable smartphones

With the introduction of foldable smartphones, research on the interaction with these devices has begun to gain interest. An investigation was conducted to examine the effects of varying folding or unfolding angles of foldable smartphones on users' privacy concerns during usage. The findings indicated that the larger screens of foldable smartphones may potentially give rise to supplementary privacy breaches (Jang, 2021). Lee *et al.* (2019) conducted experiments to investigate user preferences for creases in foldable smartphones. The study revealed that the dimensions of a user's hand do not have an impact on their inclination towards the crease feature in foldable smartphones. However, the specific characteristics of the task at hand significantly influence the users' selection of the folding method. Tan *et al.* (2023) conducted interviews to examine the anticipated gesture interactions with foldable smartphones among both current and prospective users. Consistency in interaction has been found to have a substantial impact on users' perception of the UX of foldable smartphones. Specific

interface optimizations are necessary for foldable smartphones. A recent investigation conducted by Dai *et al.* (2023) revealed that the utilization of split keyboards in the unfolded mode of foldable smartphones yields notable reductions in input errors and typing time when compared to unoptimized input methods. This finding underscores the imperative for manufacturers to exert additional efforts in order to enhance the UX. While researchers have studied UX aspects of foldable smartphones, these studies focus on specific features, leaving a comprehensive UX framework unaddressed.

These existing studies reveal three critical gaps in current foldable smartphone UX research: First, the fragmented approach—where studies focus on isolated aspects such as privacy concerns (Jang, 2021), crease preferences (Lee *et al.*, 2019), or input methods (Dai *et al.*, 2023)—lacks integration into a comprehensive framework that captures the unique technological UX elements specific to foldable devices. Second, there is insufficient attention to the hinge as a central UX determinant, despite its fundamental role in distinguishing foldable smartphones from conventional devices. Third, existing research lacks systematic validation methods to demonstrate how proposed UX elements actually influence user satisfaction and device usability. These gaps necessitate a holistic framework that specifically addresses the technological UX unique to foldable smartphones, with the hinge as the focal point, supported by empirical validation.

### 2.3. Research method

Based on the literature review, this study defines the UX of foldable smartphones as all direct and indirect experiences that users have while interacting with foldable smartphones. Moreover, this study situates the hinge, an essential element of foldable smartphones, as the central focus of the UX for these devices. It posits that the technological UX encountered by users of foldable smartphones primarily stems from the direct and indirect characteristics of the hinge, as well as its associated designs or services. The UX of foldable smartphones is influenced by various factors, including their visual design and hardware specifications. Nevertheless, this study does not explicitly address the elements that fall under the concept of general UX, as they primarily correspond to the UX framework observed in conventional smartphones and tablets. Instead, it focuses solely on the technological UX of foldable smartphones, with the hinge serving as the central component. This focus on technological UX addresses the identified research gaps by providing a systematic framework that integrates the fragmented aspects of foldable smartphone interaction into three core elements centered around the hinge. Unlike previous studies that examine isolated features, this framework captures the interdependent relationships between hinge design, user characteristics, and interface adaptations that collectively define the foldable smartphone experience.

This study uses a step-by-step mixed-methods approach. Each phase builds on findings from the previous phase. Phase 1 (product survey) identified manufacturer priorities and hinge-focused design trends. Phase 2 (user feedback analysis) revealed real-world UX problems, validating manufacturer concerns and uncovering additional user issues. Phase 3 (use case studies) provided detailed behavioral observations of how users actually interact with foldable devices in different contexts. Phase 4 (expert brainstorming) synthesized empirical findings from Phases 1-3 into coherent framework elements. Phase 5 (literature validation) confirmed each framework element's theoretical foundation and UX impact. This sequential design ensures that the framework is grounded in both empirical evidence and theoretical knowledge. Finally, a case study demonstrates the framework's practical application and validation approach.

## 3. DEVELOPMENT OF UX FRAMEWORK

As shown in Figure 1, this study proposes a UX framework for foldable smartphones composed of three core elements: the hinge, the user, and the folding-state interface, which refers to interface optimization for folding and unfolding states. The interdependence of individual elements within the framework for foldable smartphones can collectively shape the UX. This study utilized the research steps outlined in the subsequent sections to acquire the proposed framework.

### 3.1. Survey of foldable smartphone products

This study examined current and upcoming foldable smartphone products, utilizing their official websites to identify their folding mechanisms. The study also collected information on the distinctive features of these products or the values they could offer to users, as this is the aspect of UX that has the greatest impact on users (Palviainen and Väänänen-Vainio-Mattila, 2009). Analysis of twelve foldable smartphones from seven brands (Table 1) reveals that the hinge mechanism is widely acknowledged as a critical factor in enhancing UX. The improvements made to this mechanism primarily revolve around enhancing flatness, smoothness, and the folding action. The hinge's significance lies in its ability to connect ergonomic design with functional reliability. Additionally, the distinction between vertical-folding models, which prioritize design aesthetics, and inward-folding models, which prioritize multitasking capabilities, suggests a deliberate approach by manufacturers to accommodate diverse consumer preferences.

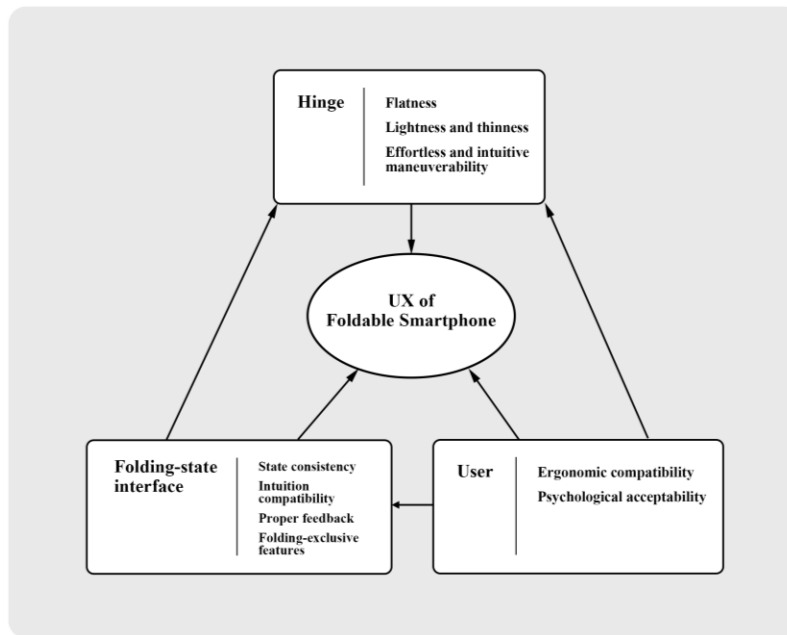


Figure 1. Foldable smartphone UX framework

Table 1. Foldable smartphone product survey categorized by model, type, and values

Brand	Model	Type of folding	Values
SAMSUNG	Galaxy Z Fold 5	Inward folding	Lightweight; Advanced hinge; Performance; Multitasking; Accessories
HUAWEI	Galaxy Z Flip 5	Vertical folding	Compact; Personalization; Large external screen
	Mate X5	Inward folding	Performance; Advanced hinge; Slim; Software ecosystem; Antenna engineering
OPPO	Pocket 2	Vertical folding	Aesthetics; Design; Advanced hinge
	Mate Xs 2	Outward folding	Slim; Sleek; Reliable; Software ecosystem
	Find N3	Inward folding	Compact; Imaging; Privacy
vivo	Find N3 Flip	Vertical folding	Compact; Standard-ratio external screen; Imaging
	X Fold2	Inward folding	Imaging; Performance; Durable Hinge; Multitasking
Xiaomi	X Flip	Vertical folding	Fashionable; Sturdy Hinge; Imaging
HONOR	MIX Fold 3	Inward folding	Hinge Design; Imaging; Software Interaction
	Magic V2	Inward folding	Lightweight; Smooth and Stable Hinge; Software Optimization
Google	Pixel Fold	Inward folding	Lightweight; Compact; Sturdy Hinge

The twelve foldable smartphone models were selected based on market representation and technological diversity criteria. The selection included products from seven major manufacturers representing approximately 85% of the global foldable smartphone market share as of 2023. The sample includes all three folding types (inward, outward, vertical) and covers different price segments (premium, mid-range) to ensure a comprehensive representation of current foldable smartphone technologies and user experiences across diverse market segments.

To systematically collect user feedback on foldable smartphone UX issues, this study employed a structured data collection approach across multiple platforms. Two major e-commerce platforms (Taobao, JD.com) and four social media platforms (Weibo, Bilibili, Zhihu, and the Rednote) were selected based on their high user engagement with technology products. Data collection focused on user reviews and discussions about the 12 foldable smartphone models identified in Table 1, spanning 12 months (January 2023 to December 2023). Search terms included product names combined with keywords such as "user experience," "problems," "issues," "hinge," "screen," and "usability." A total of 847 user comments and reviews were collected. Data cleaning involved removing duplicate posts, non-English content (unless translated), and

posts shorter than 10 words. Word frequency analysis was conducted using Python's NLTK library, with manual categorization of issues based on semantic similarity and expert judgment to create the categories shown in Table 2.

Table 2. Survey on UX issues in foldable smartphones reported by users

Category	Sub-category	Frequency	Description
Hinge	Durability and design	48	Visible fold marks; Central screen cracking at the hinge; Uneven wear
	Loosening and noise	34	Hinge loosening, noise, and causing unevenness when the device is unfolded
	Folding and unfolding	27	The device requires considerable effort to fold or unfold, indicating a lack of smoothness in hinge movement.
	Springiness	13	A pronounced spring-like feel when folding or unfolding the device, detracting from a smooth transition
Screen	Quality	44	Screen discoloration, pixelation, and visibility of fold marks are affecting display quality
	Durability	12	Screen scratches, bubbling, an unresponsive touch sensor, and dead pixels
Design and Ergonomics	Weight and Size	35	Devices perceived as heavy and uncomfortable for one-handed use
	Screen Harmony	18	Mismatch in screen resolution and size between internal and external displays
Interface and Software	UI Adaptation	30	UI not well adapted to the foldable format, leading to usability issues
Performance	Crashes	6	Frequent software crashes and low app compatibility
	Heating	21	Overheating during charging, gaming, video, and filming, causing discomfort and potential damage
	Battery and Lag	16	Fast battery drain, slow charging, and performance lag during multitasking
Others	-	10	Screen protector bulging; separation of the screen from the frame

### 3.2. Use cases study and task analysis

Building on the product survey findings that highlighted hinge importance and user concerns, this study next examined actual user behaviors through detailed case studies. Following the survey, this study conducted a series of use case studies to obtain a more comprehensive understanding of the UX of foldable smartphones in various usage contexts or tasks. Five researchers with expertise in foldable smartphones and human-computer interaction participated. A vertical or horizontal folding smartphone was allocated to each participant for uninterrupted usage for a duration of two weeks. The five participants (3 male, 2 female) were researchers aged 23-34 years with expertise in human-computer interaction and UX design. All participants held advanced degrees in related fields and had at least 3 years of experience in mobile technology research. Participants were selected based on their professional background to ensure informed observations and articulate documentation of UX phenomena. Each participant was provided with at least a vivo X Fold2 (n=3) or vivo X Flip (n=3) to ensure coverage of both horizontal and vertical folding mechanisms. Their task procedures, usage scenarios, and user perceptions through the utilization of a photo diary approach were recorded. Examples of task analysis are provided in Table 3. The task flows were deconstructed and grouped for subsequent analysis based on the types of tasks and execution steps.

Table 3. Examples of task analysis

Task	Task steps	Scenario	Impressions
Taking photos	Open the camera - Rotate and fold the phone to 90 degrees - Adjust the angle according to the viewfinder frame - Click to take a photo.	Outdoor; Standing	Success: High, the task was completed well without errors. Effort: Low, but required the subject to adjust and hold the phone at a certain angle. Satisfaction: Good, the interaction was novel,

Task	Task steps	Scenario	Impressions
Gaming	Expand the phone - Rotate to landscape orientation, camera facing downwards - Open the game.	Indoor; Sitting	but there was a certain learning curve. Success: High, task completed successfully; Effort: Low, only required to unfold the phone; Satisfaction: Moderate. The phone's uneven weight distribution makes the grip unstable.
Taking notes	Open note app - Rotate and fold the phone to a laptop-like angle - Type on the lower half of the screen, acting as a keyboard to record notes.	Indoor; Sitting	Success: Low, abandoned after a short period of use; Effort: High, high rate of keyboard mispresses, unclear display of recorded content, uncomfortable typing experience; Satisfaction: Low, did not achieve the purpose at all, very poor experience.

The coding process followed these specific steps: (1) Initial reading of all diary entries to understand overall content, (2) Line-by-line coding where two researchers independently labeled text segments with descriptive codes, (3) Code comparison meetings where researchers discussed differences and refined definitions, (4) Final coding round applying agreed-upon codes to all entries, and (5) Pattern identification where similar codes were grouped into the three main categories. Each diary entry contained an average of 3-5 task observations with accompanying photos and reflective notes.

The initial examination of the photo diary indicates that, apart from dynamic activities necessitating the act of hovering at specific angles, static activities like gaming also entail the act of folding and unfolding the phone. This finding provides additional evidence supporting the notion that the folding and unfolding process of foldable smartphones plays a pivotal role in shaping the UX. Contrarily, as per the theory of human-machine-environment interaction, distinct users will consistently engage with the machine in varying environmental circumstances, encompassing the physical environment, task environment, and software guidance. This phenomenon can also elucidate the divergent expectations held by users with regard to foldable smartphones, consequently leading to the perception of distinct UX.

### 3.3. Deriving elements of foldable smartphone UX

The use case studies revealed specific interaction patterns and UX challenges. To synthesize these empirical findings into a structured framework, expert brainstorming sessions were conducted. Eight experts took part in brainstorming sessions. The group included: two university professors specializing in human-computer interaction (with 8-15 years of academic experience), four UX researchers from the use case studies, and two senior product designers from major technology companies with 5-12 years of industry experience in mobile device design. The brainstorming sessions followed a structured approach: (1) individual idea generation based on product survey findings and use case results, (2) group discussion and clustering of ideas using affinity mapping, (3) synthesis of ideas into framework elements through collaborative analysis, and (4) validation of element definitions through consensus-building discussion. Sessions were audio-recorded and transcribed, with framework elements derived through thematic analysis of expert discussions and validated through member checking with all participants. These sessions aimed to identify the key elements of the UX framework for foldable smartphones. Brainstorming is a systematic process that uses relevant information to achieve usability goals by encouraging knowledge sharing among experts and promoting group learning (Wilson, 2013). Table 4 presents the derived elements, sub-elements, descriptions, and corresponding design concepts or variables for the foldable smartphone UX framework, based on the foldable smartphones provided during the brainstorming session, previous product research, and case study results.

Table 4. Elements, descriptions, and corresponding concepts or variables of the UX framework

Element	Sub-element	Description	Design Examples	Concept or variable
Hinge	Flatness	Guarantees a seamless screen even after numerous folds, without creases, enhancing visual continuity and content display	Samsung's UTG (Ultra Thin Glass) technology, HUAWEI's multi-dimensional hinge, and reducing crease visibility	Hinge Architecture, Material Science
	Lightness and	Ensures the hinge design contributes to	vivo's aerospace-	Material Science

Element	Sub-element	Description	Design Examples	Concept or variable
	thinness	the overall lightness and slim profile of the device, making it more portable and comfortable to use without compromising durability	grade materials; OPPO's precision-engineered titanium components	
	Effortless and intuitive maneuverability	Facilitates effortless folding and unfolding that aligns with user force habits, and allows the device to stay put or snap into place at essential angles for ease of use	Samsung's cam-based mechanism with magnetic closure; Xiaomi's liquid metal hinge with custom torque curves	Damping; Torque, Friction; Stiffness
User	Ergonomic compatibility	Matches device design to user hand size, grip strength, and typical usage patterns to minimize discomfort and enhance long-term UX	Adjustable grip zones; Variable thickness design accommodating different hand spans	Hand Size; Grip Strength; Finger Range of Motion
	Psychological acceptability	Addresses user comfort with the device by balancing low learning curves, high tolerance for errors, and openness to innovation, ensuring the technology is approachable and easily adopted	Gradual feature introduction; Tutorial systems; Error recovery mechanisms	Trust; Acceptance; Tolerance
Folding-state interface	State consistency	Maintains uniformity in content presentation, display, and transition logic between folded and unfolded states, ensuring a seamless UX across all modes of operation	Android's Screen Continuity API; Samsung's One UI fold-aware layouts	Cross-Platform Compatibility; UI/UX Design Principles
	Intuition compatibility	Incorporates interactions that align with users' mental models, ensuring interface behavior feels intuitive and matches expectations for a more natural UX	App continuation across screens; Familiar gesture mappings	Mental Model; UI/UX Design Principles
	Proper feedback	Utilizes design elements like sound or visual to mark the folding or unfolding process, improving the UX by making the action more intuitive and engaging	Haptic responses during folding; Audio cues for screen transitions	Auditory Feedback; Visual Feedback; Tactile Feedback
	Folding-exclusive features	Integrates unique functionalities accessible only in the folded state, enhancing utility and user engagement by offering specialized tasks or apps	Flex mode photography; Split-screen multitasking; Cover screen quick actions	UI/UX Design Principles

The hinge plays a pivotal role in the design of foldable smartphones, serving as a fundamental element that influences both the device's functionality and UX. The significance of the hinge resides in its capacity to maintain uninterrupted screen continuity, even when subjected to multiple folds, without the formation of creases. This, in turn, enhances both visual continuity and the display of content. In addition, the design of the hinge plays a significant role in enhancing its overall weight and slim profile, thereby improving portability and user comfort while maintaining durability. The hinge's folding and unfolding mechanisms are designed to be effortless, intuitive, and in line with the user's force habits. This ensures that the hinge remains in place or can be quickly snapped into place at important angles.

Furthermore, it is essential to prioritize ergonomic compatibility by customizing the design to match the user's hand size, grip strength, and typical usage patterns. This minimizes any potential discomfort and improves the overall UX in the long run. Psychological acceptability pertains to the provision of user comfort through the careful consideration of factors such as low learning curves, high error tolerance, and openness to innovation. This approach aims to ensure that the technology is accessible and readily embraced by users.

Regarding the folding-state interface, the preservation of state consistency is upheld in the presentation of content, display, and transition logic between folded and unfolded states, thereby guaranteeing a smooth UX across all operational modes. Its interactions are designed to correspond with users' cognitive models, guaranteeing intuitive behavior for a more

authentic UX. Effective feedback mechanisms, such as auditory or visual cues, indicate the process of folding or unfolding, enhancing the intuitiveness and engagement of the action. Additionally, folding-exclusive features integrate unique functionalities accessible only in the folded state, further enhancing utility and user engagement by offering specialized tasks or apps that leverage the compact form factor. Examples include a laptop-like video watching experience, a makeup mirror function, among others, enriching the foldable smartphone experience with specialized functionality.

#### 4. IMPACT OF FRAMEWORK ELEMENTS ON FOLDABLE SMARTPHONE UX

Having identified the three core framework elements through empirical research and expert synthesis, the next step involved validating these elements through literature analysis to understand their theoretical foundations and UX impacts. This section examines the three framework elements as distinct components and analyzes their influence on foldable smartphone UX through a literature review. Additionally, the study aims to offer design or optimization recommendations.

##### 4.1. Hinge

The hinge, in its varied forms, such as the U-shaped and teardrop-shaped configurations (Hwang *et al.*, 2021), assumes an undeniable prominence. The folding process is significantly influenced by its parameters and design characteristics, which in turn have a profound impact on the user's interactions with it. The folding action of foldable smartphones can be analyzed similarly to any physical motion. This analysis involves three distinct stages: early acceleration, mid-maintaining speed, and late deceleration (Lee, 2015). The quality and fluidity of these stages are directly influenced by the attributes of the hinge, including damping, torque, and friction, thus directly impacting the UX (Li *et al.*, 2013; Wang *et al.*, 2019; Huo *et al.*, 2021; Peng *et al.*, 2021). In addition to its mechanical properties, the hinge also plays a crucial role in maintaining the structural integrity of the device. Ensuring the security and stability of the device in its closed state requires the strategic placement of magnets along the screen edges, which are closely intertwined with the hinge's functionality. The UX becomes more intricate as the magnets require an extra force during the early stages of the unfolding process and provide a quick and conclusive closure towards the end, factors that require careful review.

##### 4.2. Folding-state interface

The introduction of a "secondary screen" in foldable smartphones, which is distinguished by the large display in horizontal foldable devices and the smaller, or even non-rectangular, screen in vertical foldable smartphones, requires a thorough examination of content layout. Research by Bruijn *et al.* (1992) has demonstrated that factors such as text layout and screen size profoundly impact reading efficiency, with specific attention to the length of a text line significantly influencing reading speed, as highlighted by Dyson (2004). Meanwhile, adopting a columnar layout emerges as an effective means to enhance the reading experience, as corroborated by Nebeling *et al.* (2011); Pinandito *et al.* (2017). For vertical foldable smartphones with smaller or irregularly shaped screens, studies recommend heightened consideration of aesthetics, symmetry, and a harmonious balance between visual appeal and display efficiency in content presentation (Wang *et al.*, 2021).

While the Android system features inherent "Screen Continuity" support (Vasan, 2020), many manufacturers and applications fall short in appropriately adapting to the transitions between small and large screens. Achieving natural transitions requires the real-time synchronization of folding progress on the screen, aligning visual feedback with the actual folding angle, thereby enhancing the UX (Li and Chen, 2019) and infusing a gratifying dimension into the folding process. Ensuring content consistency in a cross-screen environment has also garnered extensive attention, encompassing elements such as moving content congruent with the folding motion (Seok, 2015), retaining key elements while judiciously duplicating or augmenting content (Levin, 2014), and rearranging content or adapting its dimensions (Li *et al.*, 2022). Different content types may require specialized interface optimization solutions, with immediacy serving as a key classification criterion (Karlson *et al.*, 2010).

##### 4.3. User

From a physiological standpoint, foldable smartphones entail alterations in the size of the screen, which in turn affect the way users grip their phones (Bergstrom-Lehtovirta and Oulasvirta, 2014). Consequently, these changes may result in both physical and mental exhaustion. Research has indicated that users with smaller hand sizes experience a reduced clickable area on their phones, which in turn increases the probability of accidental touches (Scott and Conzola, 1997; Zhang *et al.*, 2015). This is primarily due to the fact that when the width of the phone screen exceeds 116mm, it becomes unfeasible for users with smaller hands to cover all areas with both hands (Oulasvirta *et al.*, 2013). Gustafsson *et al.* (2018) discovered a negative correlation between hand size and grip strength and hand discomfort. This suggests that smaller hand sizes may lead to increased

operational difficulties and discomfort due to the need to stretch fingers while holding the phone (Lee *et al.*, 2016). These studies suggest that users with smaller hand sizes may struggle to operate larger screens, leading to a negative experience. Gender is a factor similar to hand size, with male hand sizes generally larger than female hand sizes with stronger hand grip (McFadden and Shubel, 2002; Nicolay and Walker, 2005; Leyk *et al.*, 2007).

The acceptance of innovative products by users is primarily influenced by their mental model, which may inadvertently disregard the psychological pressure associated with the novelty and excitement of product usage (Juaneda-Ayensa *et al.*, 2016; Gkinko and Elbanna, 2022). Additional factors that users must endure include the learning curve resulting from varying operating systems and designs (Park and Koo, 2016), as well as concerns regarding privacy and security. Concerns have been raised regarding horizontal foldable smartphones due to their larger screen size and unconventional design, which inherently leads to content leakage problems in public areas (Zhou *et al.*, 2015; Moreham, 2006). The reciprocal relationship between user openness and tolerance for innovative products has been observed, whereby users with lower levels of openness tend to display lower levels of tolerance towards innovative products, as evidenced by their resistance behaviors (Nov and Ye, 2008).

## 5. CASE STUDY: THE IMPACT OF HAND SIZE ON THE UX OF FOLDABLE SMARTPHONES

The UX of foldable smartphones is influenced by the user's ergonomic compatibility, as stated in the proposed framework for foldable smartphones. This case study serves as an exploratory investigation to demonstrate the framework's applicability, investigates the influence of users' hand sizes on the UX of foldable smartphones by conducting an experiment. This case study employs an exploratory research approach, focusing on pattern discovery and insight generation rather than hypothesis testing. Given the emerging nature of foldable smartphone technology, this exploratory investigation aims to uncover initial evidence of user differences that can guide future confirmatory studies with larger sample sizes and more rigorous experimental controls.

This experiment specifically validates the "User" element of the proposed framework, focusing on ergonomic compatibility identified in Table 4. The framework established that user characteristics—particularly hand size, grip strength, and finger range of motion—significantly influence foldable smartphone UX through their interaction with hinge mechanisms. The experimental design operationalizes this theoretical relationship by comparing users with different hand sizes during folding tasks, measuring both objective pressure data and subjective fatigue responses.

The validation approach demonstrates how framework elements interconnect to influence UX outcomes. By examining user-hinge interactions during folding tasks, this case study provides empirical evidence for the framework's prediction that ergonomic mismatches between user characteristics and device design result in measurable UX differences, moving beyond the isolated feature analyses found in previous foldable smartphone research.

### 5.1. Experimental design

The independent variable for the experiment is the participants' hand size, categorized into large and small, serving as a between-group variable. This variable directly corresponds to the framework's "User" element, specifically testing the ergonomic compatibility sub-element (Table 4), which identifies hand size as a critical design variable affecting foldable smartphone UX. The dependent variable, UX of the foldable smartphone, was measured by the pressure applied by fingers on the foldable smartphone and subjective fatigue reported by the participants during tasks. These measurements operationalize the framework's prediction that ergonomic mismatches between user characteristics and device design result in increased physical demands and reduced user satisfaction. The pressure measurements capture the interaction between the "User" and "Hinge" elements, while fatigue assessments reflect the overall UX impact predicted by the framework.

The experimental task involved vertically folding an inward-folding smartphone. The vivo X Fold2 was selected as the experimental device due to its representative hinge design characteristics, standard form factor among inward-folding devices, and consistent availability for controlled experimental conditions. Vertical folding involves facing the phone gap vertically and simultaneously folding and unfolding both screens horizontally using both hands. Since the individual folding time is short, the experimental task requires participants to maintain the folding action for 3 minutes at their self-selected pace to accumulate experience differences.

The pressure sensor for measuring finger pressure on the phone employs the FSR400, with a measurement range of 0 to 10000 g and an accuracy of 0.1 g. The pressure point locations shown in Table 5 are determined through task analysis from use case studies, expert interviews, and pre-experiments. The Borg Fatigue Scale (Borg, 1982) was used to measure participants' subjective fatigue, consisting of a 0 to 10 scale where lower scores indicate less fatigue, including 0.5, indicating "just noticeable fatigue". Its advantages include effective real-time fatigue measurement, wide applicability, high timeliness, and simplicity.

Table 5. The pressure point design

Number	Location	Finger interacting point
1	Right folding corner, 6 cm above the bottom of the device.	Right thumb
2	Left folding corner, 5 cm above the bottom of the device.	Left thumb

## 5.2. Procedure and participants

Upon the arrival of participants and their completion of the informed consent form, the experimenter proceeded to elucidate the experimental procedure. Participants were given a time frame of 3 to 5 minutes to engage with the foldable smartphone and become acquainted with the task. During this time, they calibrated the baseline of the Borg scale. The formal experiment was initiated, consisting of a continuous 3-minute folding task. The participants adhered strictly to the prescribed posture throughout the task, ensuring that their key fingers maintained consistent contact with the locations of the pressure sensors. Participants provided the experimenter with their current Borg fatigue scale values at the 1st, 2nd, and 3rd minutes of the folding task. Ultimately, the hand size attributes of the participants were assessed by measuring their hand length, hand width, and index finger length. The duration of the experiment ranged from 15 to 20 minutes, and each participant received compensation OF 15 CNY.

This exploratory study employed N=14 participants following established practices in ergonomic research for initial investigations of hand size effects on device interaction (Gustafsson *et al.*, 2018; Zhang *et al.*, 2015). As an exploratory investigation designed to demonstrate the framework's applicability rather than provide definitive population estimates, this sample size allows for pattern detection and insight generation. The controlled laboratory conditions and repeated measures design (pressure measurements every 30 seconds over 3 minutes) enabled the detection of meaningful differences between hand size groups. Future confirmatory studies should employ larger sample sizes to establish population-level generalizations.

The recruited participants had equal distribution of genders and an average age of  $20.83 \pm 1.21$  years, respectively. In relation to hand size, the Chinese Adult Body Size GB 10000-88 was utilized as a reference. Participants with hand sizes exceeding the 90th percentile were categorized as large-handed, while those with hand sizes below the 50th percentile were categorized as small-handed. Consequently, a total of seven participants were classified as large-handed, with an average hand length of  $195.83 \pm 10.71$  mm, and 7 participants were classified as small-handed, with an average hand length of  $170 \pm 7.43$  mm. Every participant was right-handed.

## 5.3. Results

Regarding the pressure exerted by the fingers on the phone, the large-handed participants demonstrated significantly higher pressure values (averaging 10-15g vs. 5-8g for small-handed participants) and greater fluctuation amplitude at the two touchpoints compared to the small-handed participants ( $P$  value  $< .01$ ). This finding suggests that users with larger hand sizes exert greater force during the process of folding and unfolding the phone, resulting in increased physiological fatigue and subsequently leading to a decline in the UX of foldable smartphones. In terms of subjective fatigue, there was no significant difference between the subjective fatigue levels of participants who used both hands ( $4.56 \pm 1.98$ ) and those who used only one hand ( $4.39 \pm 1.38$ ). However, it was observed that large-handed participants experienced higher levels of subjective fatigue compared to small-handed participants during the third minute ( $P$  value  $< .01$ ). This finding aligns with the conclusions drawn from the pressure results. Table 6 displays the descriptive results. The pressure experiences fluctuating cycles that are influenced by the subjects' ability to fold and unfold the phone, thereby excluding the variability observed at specific time intervals.

Table 6. The descriptive values of pressure and fatigue of big and small hand-size users over time

Variable	Time (s)	Value	
		Small hand-size	Big hand-size
Pressure (g)	30	60.67	80.00
	60	48.00	78.17
	90	22.33	65.50
	120	60.67	84.67
	150	55.83	59.33

Variable	Time (s)	Value	
		Small hand-size	Big hand-size
Fatigue	180	38.83	61.17
	60	3.50 ± 1.38	3.33 ± 1.37
	120	4.50 ± 1.22	4.33 ± 1.75
	180	5.17 ± 1.17	6.00 ± 2.00

The folding and unfolding task lasted for 3 minutes. Figure 2 presents the pressure changes over time using moving averages to highlight underlying trends, with confidence intervals indicating variability within each group. The pressure values demonstrate clear differences between hand-size groups throughout the experimental period. Participants with larger hands exhibited consistently higher pressure application, starting at approximately 80g and maintaining elevated levels (55-70g) for most of the task duration. In contrast, participants with smaller hands showed more variable but generally lower pressure values, ranging from 40-60g with notable fluctuations throughout the task.

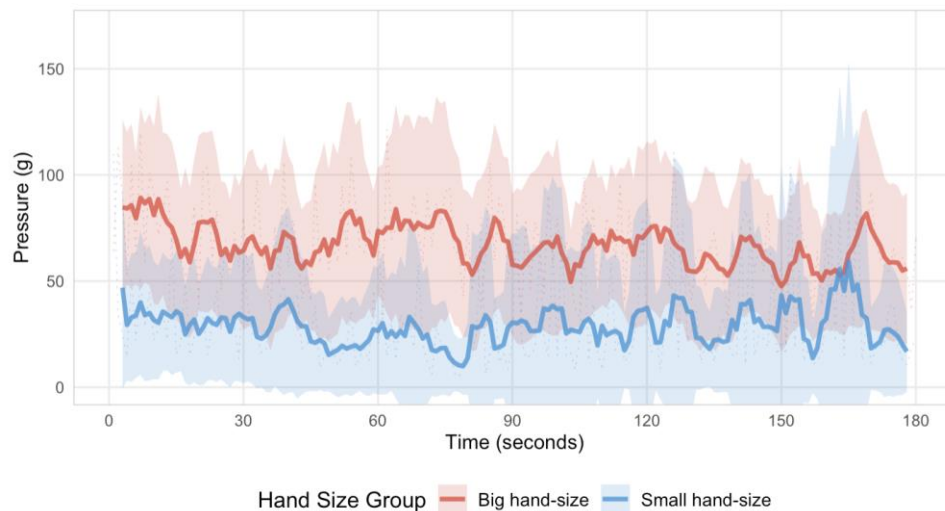


Figure 2. Pressure changes over time during the 3-minute folding task (n=7 per group).

Solid lines: Moving average (5-point window); Dotted lines: Raw data; Ribbons: 95% CI

Small hand-size group: hand length  $170 \pm 7.43$ mm; Big hand-size group: hand length  $195.83 \pm 10.71$ mm.

Figure 2 demonstrates distinct pressure patterns and adaptation behaviors between hand-size groups during the 3-minute folding task. The big hand-size group applied consistently higher pressure with relatively stable values around 60-65g, while the small hand-size group exhibited greater variability with pressure fluctuations between 40-60g and wider confidence intervals. Both groups show convergence toward similar pressure levels (~45-50g) in the final portion of the experiment, suggesting adaptation to the folding task. However, the sustained higher pressure application by larger-handed users throughout most of the task (approximately 10-15g higher on average) indicates increased physical demand when interacting with the current hinge design, supporting the framework's emphasis on ergonomic compatibility as a critical UX factor. In general, the pressure data and subjective fatigue data indicate that the UX of foldable smartphones for users with larger hands was initially worse to that of users with smaller hands. However, over the course of the task, the level of UX for participants with small hands gradually diminished, while the UX of both groups reached a comparable level.

These experimental results provide empirical validation for key aspects of the proposed UX framework. The significant pressure differences between hand size groups directly validate the framework's "User" element, confirming that ergonomic compatibility is a measurable UX determinant. The sustained higher pressure application by larger-handed participants throughout the folding task supports the framework's theoretical prediction that mismatched user-device ergonomics lead to increased physical demands and potentially degraded UX. The results also validate the interconnected nature of framework elements. The pressure variations demonstrate how user characteristics (hand size) interact with hinge design to influence UX outcomes, supporting the framework's emphasis on element interdependence rather than isolated factor analysis. The adaptation patterns observed over the 3-minute task period further validate the framework's inclusion of psychological acceptability factors, as users with initially poor ergonomic matches showed learning and adaptation behaviors.

This validation demonstrates the framework's utility for systematic UX assessment. Unlike fragmented studies that examined isolated foldable smartphone features, this experiment shows how the framework's integrated approach can identify specific user-device mismatches and predict their UX impacts, providing manufacturers with actionable design guidance for improving ergonomic compatibility in future foldable devices.

## 6. DISCUSSION

The case study outcomes affirm the proposed UX framework's comprehensive and systematic approach to understanding UX with foldable smartphones. The practical application of the UX framework has demonstrated its utility in systematically collecting and analyzing UX across different models of foldable smartphones. The framework facilitated detailed user feedback on specific aspects, such as hinge design, screen continuity, and ergonomic factors, which are pivotal in shaping the overall UX. Device manufacturers can utilize this framework for product planning assessments to achieve foldable smartphones that more closely align with user habits and expectations. Researchers can design experiments based on the variables provided in the framework to conduct scientific inquiries surrounding foldable smartphones.

This research makes three key theoretical contributions to the UX and human-computer interaction literature, each representing distinct advances over existing approaches. First, this study established the concept of "technological UX" for foldable smartphones, contrasting with traditional UX frameworks. Unlike ISO 9241-210's general UX definition focused on software interfaces (Mirnig *et al.*, 2015) or existing mobile UX research emphasizing screen size and resolution (Raptis *et al.*, 2013; List and Kipp, 2019), this framework identifies hardware design elements—specifically the hinge mechanism—as primary UX determinants. This differs significantly from conventional smartphone UX studies where hardware factors are secondary to software interfaces (Anderson *et al.*, 2010; Lin *et al.*, 2018). The framework advances UX theory by demonstrating how physical form factor changes create entirely new UX dimensions requiring specialized theoretical approaches.

Second, this study contributes a systematic integration methodology that addresses the fragmentation problem in current foldable smartphone research. Previous studies examined isolated aspects: Jang (2021) focused solely on privacy concerns, Lee *et al.* (2019) studied only crease preferences, and Dai *et al.* (2023) addressed input methods exclusively. This fragmented approach fails to capture the interdependent relationships between foldable device elements. In contrast, this framework synthesizes these disconnected insights into three interconnected elements: hinge, user, and folding-state interface. Unlike existing technology acceptance models (Holden and Karsh, 2010; Lee *et al.*, 2003) that treat device characteristics as static variables, this integration model recognizes dynamic interactions between hardware design, user characteristics, and interface adaptations.

Third, this research extends ergonomic theory beyond traditional static form factors to dynamic device geometries. Conventional ergonomic studies focus on fixed device shapes where users adapt to unchanging hardware configurations (Gustafsson *et al.*, 2018; Zhang *et al.*, 2015). However, foldable smartphones require users to actively manipulate device geometry during use, creating new ergonomic challenges absent in traditional mobile devices. This study's emphasis on ergonomic compatibility for folding actions represents a theoretical advancement in understanding how human factors principles apply to transformative technologies where device form changes during interaction.

Unlike these isolated approaches, this study provides three specific improvements: 1. Systematic Integration: The three-element framework captures interdependencies between hardware, user, and interface factors that previous studies examined separately. 2. Hinge-Centered Approach: This research identifies the hinge as the central technological differentiator, whereas previous studies treated it as a peripheral factor. 3. Empirical Validation Methodology: The framework includes validation approaches through controlled experiments, addressing the gap in systematic testing methods present in prior research. The framework also advances beyond general UX research by addressing technology-specific factors. Traditional UX frameworks often focus on software usability metrics applicable to conventional devices, while this study identifies unique hardware-driven UX elements specific to foldable technology. This represents a methodological improvement where framework development is grounded in technology-specific empirical research rather than adapted from general UX principles.

This framework also provides actionable guidance for multiple stakeholders. Device manufacturers can use the framework to systematically evaluate design decisions, prioritizing hinge improvements that directly impact UX. The framework's specific variables (damping, torque, and friction) offer measurable targets for engineering teams. Software developers can apply the folding-state interface principles to create more intuitive cross-screen experiences. UX researchers gain a validated tool for studying foldable devices, enabling systematic comparison across different designs and user groups.

Since foldable smartphones are mobile devices, factors that affect the UX of regular phones will also impact the UX of foldable smartphones. Examples include hardware design factors like screen size, resolution, and refresh rate (Raptis *et al.*, 2013; List and Kipp, 2019; Zinner *et al.*, 2010), as well as design factors like software fluency and user interface (Lin *et al.*, 2018; Anderson *et al.*, 2010). This framework focuses on factors distinct from traditional phones that specifically affect foldable smartphone UX, such as the hinge. Therefore, the general factors that should that can be categorized as general UX

are included in the framework, for this framework is more of a technological UX centered around the hinge, according to Jang and Han (2022). Similarly, environmental factors are crucial for influencing UX, including objective environmental parameters (temperature, humidity, etc.) and the user's task environment (location, time, etc.) (Schmidt, 2000; Preece *et al.*, 1994). However, the usage environment of foldable smartphones does not extend beyond that of regular smartphones, so the framework does not consider environmental factors and instead focuses on task factors that present more possibilities due to foldable smartphone capabilities.

Users have different expectations or acceptance levels for devices (Szajna and Scamell, 1993; Igarria, 1993). The study has discussed the impact of user technology acceptance on product experience and, based on this, has proposed psychological factors influencing the UX of foldable smartphones. In fact, for technology subfields, researchers have proposed various technology acceptance models. Apart from the commonality that both products and users share in these models, different researchers have considered factors such as behavior, inclination, attitude, etc., influencing acceptance (Holden and Karsh, 2010; Lee *et al.*, 2003). This framework includes the user's mental model within the range of psychological characteristics. It not only aligns with extensively researched aspects by previous scholars but also plays a significant role in explaining user perceptions of foldable smartphones, reflecting current user behaviors in the foldable smartphone market.

The literature review has revealed that users with smaller hand sizes exhibit a higher susceptibility to fatigue and discomfort when engaging in stationary tasks with heavier mobile devices. Nevertheless, the empirical findings from the case study indicate that users with larger hands encounter greater fatigue. The potential explanation for this outcome could be attributed to the absence of dedicated attachment points for users' fingers during the folding and unfolding of the foldable smartphone utilized in the experiment. Hence, participants aimed to grasp the seams or apply pressure on both sides of the foldable smartphone to exert maximum force while unfolding. Participants with larger hands typically possess thicker fingers, which poses a challenge in gripping the seams or applying pressure on narrower edges, resulting in increased force exertion. This further substantiates the influence of hand size on the UX of foldable smartphones.

This study has several limitations that affect generalization. The small sample size (N=14) of the exploratory case study limits the ability to generalize findings to the broader population of foldable smartphone users. The use case study with five participants, while providing rich insights, represents expert perspectives rather than typical consumer experiences. Additionally, the experimental task focused on a single device model (vivo X Fold2) and one specific folding action, which may not represent the full range of foldable smartphone interactions. These limitations should be considered when interpreting results, and larger-scale studies are needed to confirm these preliminary findings across diverse user populations and device types. There is significant potential to expand the use of the UX framework to encompass new designs and technologies in the field of foldable smartphones. Subsequent investigations could delve into the UX by examining novel hinge mechanisms, folding patterns, and material advancements, thereby enhancing the comprehension of the correlation between technology and user contentment. Moreover, expanding the range of case studies in terms of usage scenarios can yield more comprehensive insights, thereby enabling the advancement of foldable smartphones that accommodate a diverse range of user preferences and requirements.

## 7. CONCLUSION

This study established a framework for the UX of foldable smartphones through detailed product research, use case studies, and expert evaluations. The framework focuses on three pivotal elements: the hinge, the user, and the folding-state interface. The literature review provided further elucidation on the interdependence of these elements. The hinge, serving as the central point of physical rotation in foldable smartphones, exerts a direct impact on the device's longevity and user engagement by virtue of its design and operational capabilities. The user element includes both ergonomic compatibility and psychological acceptability, which represent the various ways in which users interact and their expectations. Finally, the folding-state interface component plays a crucial role in maintaining uniformity, user-friendliness, and uniqueness throughout various states of the device. This underscores the importance of smooth transitions and flexibility in user interfaces with specialized functionalities to effectively accommodate the ever-changing characteristics of foldable smartphones. The UX framework's validity was further substantiated by conducting a case study that specifically examined the influence of hand size on the UX of foldable smartphones. This investigation emphasized both the practical consequences of the framework and the importance of considering ergonomic factors when designing and developing foldable devices.

This study established the first comprehensive UX framework specifically designed for foldable smartphones, filling a critical gap in both theory and practice. The framework's three-element structure—hinge, user, and folding-state interface—provides a systematic approach for understanding and improving foldable device experiences. By centering the framework on the hinge as a key technological differentiator, this research advances UX theory beyond traditional static device models. The framework's validation through the hand size case study demonstrates its practical utility for identifying and addressing real user differences. This work provides a foundation for future foldable technology research and offers immediate value for manufacturers developing next-generation devices.

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