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Review and Appraisal of Approaches to Assess Comfort of Wearable Devices

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ABSTRACT

In recent years, the market for lightweight wearable devices for eye-, ear-, and wrist-worn has grown rapidly. For these lightweight wearable devices, comfort directly impacts consumer adoption. However, most of the existing literature on the comfort of wearable devices have focused on wearable computers that are large in size and weight, and there is still a lack of comprehensive insights for approaches to assess the comfort of lightweight wearable devices. The present study reviewed existing research on the comfort of lightweight wearable devices, discussed the characteristics and limitations of current comfort assessment approaches, and provided feasible directions for foreseeable more extensive comfort assessment research.

Keywords: Wearables, Comfort, Measures, Review

INTRODUCTION

The size of the global wearable devices market has grown steadily in recent years and is forecast to expand at a compound annual growth rate (CAGR) of 15%-20% over the next five years. Among all types of consumer-oriented wearable devices, the wrist-worn and ear-worn product segments dominate the current global industry. Eye-worn wearable devices are also viewed as a product segment with rapid growth potential due to its expanding applications in the multimedia industry. For these types of wearable devices, comfort is one of the major influencing factors for consumers to make purchasing decisions. Therefore, comfort assessment of eye-, ear-, and wrist-worn wearable devices can help to identify users' comfort expectations, discover deficiencies in current designs, and improve the ergonomics of products.

Unfortunately, research in this area is not well developed. Most of the existing comfort assessment approaches for wearable devices originated from the early development of wearable technology, and most of the assessment objects are wearable computers with large volume and weight (Bodine and Gemperle, 2003; Knight et al., 2006). With the rapid development of lightweight wearable devices and their applications in recent years, academics have mostly focused on the prospects of their applications in health care (Dunn et al., 2018) and industrial fields (Svertoka et al., 2021), with little further research on the comfort of consumer products. However, as the physical image of wearable devices changes from bulky helmets and weighted backpacks to relatively compact forms such as wristbands, earphones, and glasses, it is doubtful whether comfort assessment approaches are still valid. On the one hand, there are inherent differences in sensory acuity and comfort thresholds in different anatomical regions of the human body (Franz et al., 2012). On the other hand, the feasibility and validity of assessment tools in different body parts and wearing scenarios need to be revalidated.

Therefore, this study will explore comfort assessment approaches for eye-, ear-, and wrist-worn lightweight wearable devices. We first summarized the current commercially available lightweight wearable products, and discussed the factors influencing the comfort of these wearable devices. Then, we reviewed existing comfort studies of lightweight wearable devices, analysed the characteristics and limitations of existing comfort assessment approaches applied to lightweight wearable devices, and provided feasible directions for the development of more comprehensive lightweight wearable device comfort assessment.

LIGHTWEIGHT WEARABLE DEVICES

Wearable devices are advanced sensors and computing technologies that can be worn on the body in everyday life (Jacobs et al., 2019). While the scope of wearables as delineated in different studies may vary, some key characteristics are generally recognized, such as unrestrictive / hands-free, controllable, mobility, and unmonopolizing (Borowski-Beszta and Polasik, 2020; ÇiÇek, 2015), which emphasize the liberation for the user's movement and attention. According to application areas, wearables can be broadly categorized into assistive, workplace, healthcare, and consumer products (Chatterjee et al., 2016). This study focuses on three of the more promising market segments in consumer products, also known as eye-, ear-, and wrist-worn wearable devices. These devices usually add new and expanded features to the traditional products. It should be noted that VR headsets are not included in this study because of their conflict with mobility and unmonopolizing. Representative products currently on the market and their attributes are shown in Table 1. All information in the table is taken from the product's official website.

Table 1. Representative products and their attributes.

Existing Products	Segmentation Attributes	Weight(g)	Size(mm)
Eye-worn			(W*H of the frame)
Epson Moverio BT-40	AR glasses, wired connection	95	194*41
Dream Glasses Flow	AR glasses, wired connection	59	160*50
Xreal air2	AR glasses, wired connection	72	148*51.4
Ray-Ban Meta Headliner	smart audio-video glasses, wireless	49.2	147.5*49.2
Snap Inc. Spectacles 3	smart audio-video glasses, wireless	56.5	153*47
Amazon echo frames 3	smart audio glasses, wireless	37.6	147*55
Ear-worn			
Airpods Pro 2	in-ear, earbuds	5.3*2	30.9*21.8*24.0
HUAWEI FreeBuds 4	semi-in-ear, earbuds	4.1*2	41.4*16.8*18.5

(Continued)

Table 1. Continued

Existing Products	Segmentation Attributes	Weight(g)	Size(mm)
Sony LinkBuds	open-ear, air condition, earbuds	4.1*2	/
Cleer ARC II sport	open-ear, air condition, ear hook	14*2	56.56*44.4*11.2
SHOKZ OpenRun Pro	open-ear, bone conduction, ear hook	29	/
Earsopen SS900	open-ear, bone conduction, ear clip	7.5*2	30.1*29.7*26.5
Wrist-worn		(Strap excluded)	
Apple Watch Ultra 2	smart watches	61.4	49*44*14.4
Huawei watch 4	smart watches	48	46.2*46.2*10.9
Gamin Forerunner 965	smart watches	53	47.2*47.2*13.2
Huawei Band 8	wrist bands	14	43.45*24.54*8.99
Fitbit charge 6	wrist bands	15	38.7*18.6*11.7

Eye-worn wearable devices mainly contain AR glasses, smart audio-video glasses and smart audio glasses. AR glasses need to be connected to accessories or terminals via data cables to be used for short periods of time in scenarios such as movie watching and gaming. Some of the glasses may be equipped with blackout lenses and generally weigh more. The latter two types of glasses usually support longer periods of wireless use in conjunction with a charging case. Of these, the smart audio glasses are the lightest, only slightly heavier than regular sunglasses.

There are many sub-categories of ear-worn wearable devices, the most common of which are closed earbuds, which contain both in-ear and semi-in-ear types. Open headphones contain both air conduction and bone conduction technology principles. Air conduction headphones contain earbuds with open rings and ear hooks that separate the left and right ears, with the ear hooks being heavier. Bone conduction headphones are mostly ear hooks that connect the left and right ears via the back of the head, except for Earpson's ear clips, which is currently the only "true wireless" bone conduction headphones that have independent left and right ears, and thus the weight can be greatly reduced.

Wrist-worn wearable devices mainly consist of smart watches and wrist bands. The dial of smart watches usually has a relatively large weight and is round or square in shape. The dial of wrist bands is usually light in weight and rectangular in shape.

FACTORS INFLUENCING COMFORT OF WEARABLE DEVICES

Comfort can be both a physical sensation and a psychological state, and its meaning is related to both "relaxation" and "absence of pain". In some studies, comfort has been defined as the absence of discomfort, i.e., unaware of negative feelings such as discomfort, fatigue, or pain (Kölsch et al., 2003). Another definition considers comfort to be a positive state that sets off positive emotional feelings (Pearson, 2009).

There are many factors that affect the user's comfort perception of wearable devices, which can be summarized from four aspects: the physical attributes of the product, intrinsic human factors, external environmental factors, and use scene and tasks. The physical attributes of the product include weight distribution, shape, contact area with the human body, material softness, hardness, breathability and thermal conductivity (Chiu et al., 2014; Park et al., 2019; Shimura et al., 2023). Intrinsic human factors include multi-channel information feedback, perceptual acuity of different body parts, variability in body size, and subjective cognitive bias (de Korte et al., 2012; Franz et al., 2012; Fu and Luximon, 2020). External environmental factors mainly include temperature, relative humidity, and wind speed (Dec et al., 2018). The use scene and task factors refer to the characteristics of the physical activities and tasks performed by the user while wearing the device (Ellegast et al., 2012; Groenesteijn et al., 2012). For example, the comfort requirements and feelings of the user may be different for office work and running.

COMFORT STUDY OF LIGHTWEIGHT WEARABLE DEVICES

Early studies on the comfort of wearable devices focused on devices that are large in size and weight, such as head-mounted display (HMD) and wearable computers. An important contribution was made by the series of studies by Knight et al. who proposed the comfort rating scales (CRS) for wearable computers, which assesses six dimensions: emotion, attachment, harm, perceived change, movement, and anxiety (Knight and Baber, 2005). Follow-up studies have also proposed the wearability levels for wearable computer systems by combining 1) heart rate, Borg RPE and CR-10 scales for assessing energy cost and fatigue; 2) the REBA method and RULA scale for assessing posture action; with 3) the CRS scale (Knight et al., 2006; Knight and Baber, 2007). However, these methods and criteria are not fully applicable to lightweight wearable devices. In recent years, related research fields have begun to focus on lightweight wearable devices, and we have compiled 12 comfort studies for eye-, ear-, and wrist-worn products, with specific experimental designs and main contributions shown in Table 2.

Current comfort studies of eye-worn wearable devices generally focus on the effects of weight and design type. Comfort studies of ear-worn wearable devices are particularly concerned with the inclusiveness of morphological differences in human ear, in addition to the impact of design type. Due to the great application potential of wrist-worn wearable devices in multiple domains, related comfort studies are often used to assess the user's acceptability in specific use scenarios rather than exploring the factors that influence user's comfort perception.

The assessment indicators used in the current comfort studies of lightweight wearable devices are, in descending order of frequency: local or overall comfort/discomfort, pressure-related sensations, pain, muscle fatigue, fit and fixation, ease of use, etc. The most commonly used measurements are the Likert scale designed by each study for its own indicators, followed by modified versions of the well-established CRS scale and the Borg CR-10 scale. In the heavily used self-designed Likert scales, each indicator assessed usually has no sub-dimensions and is measured by only 1–2 two items that have not been rigorously validated. In addition, all of the measurements mentioned above are subjective assessments, and only very few studies have used objective measurements such as electromyogram (EMG) (Chang et al., 2018), heart rate (Smith et al., 2021), pressure gauge (Yan et al., 2022), and REBA method (Cancela et al., 2014).

In terms of task design, most of the comfort studies of lightweight wearable devices have used specific laboratory-controlled tasks. For example, studies of eye-worn wearable devices commonly used static tasks (e.g., video viewing), and only one study evaluated the comfort perception in a dynamic work scenario (Smith et al., 2021). The tasks in the studies of ear-worn wearable devices involved multiple use scenarios such as office work, exercise, and sleep, but only one of these was used in each study. More unusually, a study evaluating the acceptability of wrist-worn wearable devices was not conducted in a controlled laboratory environment, but rather collected comfort feelings from 7 consecutive days of uninterrupted wear (McNamara et al., 2016). This experimental design allows for the most realistic discomfort feedback to be collected as comprehensively as possible, which is conducive to the improvements in the user experience of the product.

DISCUSSION

After analysing the existing comfort studies for lightweight wearable devices, some limitations of current comfort assessment approaches are identified, and corresponding directions for development are suggested.

Develop Refined Subjective Assessment Tools

The only established comfort assessment scale for wearable devices is the CRS scale (Knight and Baber, 2005), which assesses the perception of emotional, tactile, and motor dimensions, but lacks attention to thermal comfort and stability. The Borg CR-10 scale (Borg and Borg, 2002), which is also widely used, is essentially a scaling methodology describing category-ratio rather than a detailed assessment for comfort. Those self-designed scales usually just incorporate all the indicators of concern rather than designing the indicator structure from a holistic perspective. In addition, all of the scales mentioned above commonly assess a particular comfort indicator/dimension with only one items, which resulted in weaker reliability of the scales.

Therefore, there is a need to develop refined subjective assessment tools for lightweight wearable devices. One idea to consider is to build a multilevel structure of comfort indicators from top to bottom, encompassing comfort dimensions as comprehensively as possible and designing the scale items from sub-levels so that each comfort dimension can be assessed by multiple items. Comfort dimensions and scale items can come from professionals' brainstorming (Knight and Baber, 2005), consumers' review feedback (Song et al., 2020), or relevant research findings from other fields. For example, a series of sensory descriptors often used in fabric/garment comfort research, including tight, sticky, itchy, heavy, cold, scratchy, etc. (Kaplan and Okur, 2012). In terms of scale forms, in addition to Likert scales, Visual Analogue Scale (VAS), Numeric Rating Scale (NRS), and Verbal Rating Scale (VRS) are equally available and are capable of assessing discomfort ranging from none to severe (Pearson, 2009).

Table 2. Studies on the comfort of lightweight wearable devices.

Study	Population	Sample Size*	Independent Variables	Dependent Variables	Measurements	Tasks	Main Contributions
Eye-worn							
(Chang et al., 2018)	American, aged 24.7±2.8	10 (7M, 3F)	Novel prototype adopting three interventions	Neck muscle fatigue; Discomfort	EMG (on the splenius capitis); Borg CR-10	Wear each pair of glasses for 90min to observe 3D content.	Propose a prototype using three interventions to reduce discomfort.
(Kim et al., 2021)	Korean, aged 24.82 ± 2.2 (M), 23.5 ± 2.0 (F)	78 (50M, 28F)	Weight; The difference in R/L weight	Change perception, pressure-related; Overall comfort, perceived heaviness	Self-designed binary scale; Self-designed 9-point Likert scale	Wear each counterweight for 5min.	Identify pressure thresholds for smart glasses wearing comfort.
(Smith et al., 2021)	American, aged 19–32	48 (20M, 28F)	Design type; Task type	Comfort; Performance	CRS; Heart rate, productivity, number of adjustments	20 min logistical order picking/putting tasks for each design type.	Existing designs are less comfortable in logistics order picking and shipping tasks.
(Du et al., 2022)	Chinese (Mainland), aged 26–45	96 (48M, 48F)	Weight; Personal factors	Discomfort	Borg CR-100	1h video viewing task.	Discovered the effect of added nose load and personal factors on discomfort.
Ear-worn							
(Chiu et al., 2014)	Chinese (Taiwan), aged 21.2±2.2	198 (100M, 98F)	4 earphone model; Gender, 3 ear shape classification	Pain points; Overall comfort, fitness, load, ease of wearing	Mark pain points on the ear figure; Self-designed 5-point Likert scale	30min simulated office tasks for each model.	Identify design properties and person characteristics that can improve user comfort.
(Song et al., 2020)	Korean, aged 21–30	38 (23M, 15F)	Ear dimensions; 4 sample products	Pain, pressure, comfort, and fixation	Self-designed 7-point Likert scale	Walking or running 20min for each product.	Identified human and product factors that affect wearing comfort.

(Continues)

Table 2. Continued

Study	Population	Sample Size*	Independent Variables	Dependent Variables	Measurements	Tasks	Main Contributions
Ear-worn							
(Röddiger et al., 2021)	German, aged 27.0±3.1	14 (8M, 6F)	7 earphones with different designs	Comfort; Effects on sleep, attachment, general concerns	Modified CRS; Self-designed 5-point Likert scale	Wear every device for one night.	Existing devices are not suitable for sleep.
(Yan et al., 2022)	Chinese (Mainland), aged 18–55	30 (15M, 15F)	8 regions of the ear	PDT, MPD, MPT	Pressure between the indenter and shell	Click the mouse when they began to feel the thresholds for each ear region thrice.	Pressure sensitivity thresholds were obtained for different regions of the external ear.
Wrist-worn							
(Cancela et al., 2014)	Spanish & Greek, aged 50–70	32 (22M, 10F)	/	Comfort; Biomechanical effect; Physiological effect	CRS; REBA, Borg CR-10+Body map; Borg CR-10	Wear the system and complete all assessment tasks.	The acceptance of the telehealth system was satisfactory.
(McNamara et al., 2016)	Australian, aged 71±9	314 (160M, 154F)	/	Compliance, adverse side effects Comfort, ease of applying and removing;	Self-designed binary scale; Self-designed 5-point Likert scale	Wear the product on upper arm 24h/day for 7 days.	Compliance with product was high but discomfort and adverse side effects were present.
(Gil et al., 2018)	Korean, aged 21.6±1.8	18 (9M, 9F)	3 different finger regions; 8 different angles	Comfort	Self-designed continuous 100-point Likert scale	Repeat 5 times for each angle of each region.	Contribute the first data on the comfort of input on smart watches.
(Wang et al., 2020)	American, college-aged	47 (23M, 24F)	2 different ambient temperatures	Thermal sensation, comfort, pleasantness	Self-designed continuous 7-point/9-point Likert scale	For each temperature: total 1h with 45min acclimation period and 3 exercises.	The product alleviates thermal discomfort in indoor environments.

*M, male; F, female

Combine Subjective Assessment and Objective Indicators

Comfort can be both a physical sensation and a psychological state. This suggests that comfort assessment can either be derived through subjective self-reporting or be reflected by objective physical or physiological signals. However, the latter is rarely used in current comfort studies for lightweight wearable devices.

In addition to EMG (Chang et al., 2018), pressure (Yan et al., 2022) and heart rate (Smith et al., 2021), which have already been tried, there are many physiological signals worth exploring. For example, electrodermal activity (EDA) that reflects sweat gland secretion on the surface of the skin may be used for thermal comfort assessment (Mansi et al., 2022); eye tracking that reflects visual fatigue may be used for comfort assessment of eye-worn wearable devices (Souchet et al., 2022); electroencephalography (EEG) that reflects emotional reflections, thermal comfort, and fatigue through a variety of signal signatures has even more potential for development (Frey et al., 2015; Mansi et al., 2022; Peng et al., 2022).

However, it needs to be acknowledged that objective indicators do present greater difficulties in the comfort assessment of lightweight wearable devices. First, customized measurement devices need to be developed, such as sensor probes or patches of different sizes and shapes (Yan et al., 2022). Second, physiological signals are susceptible to noise interference, leading to higher difficulties in experimental design and data analysis. Finally, it is easy to get stuck when constructing the relationship between objective indicators and subjective assessment, because human subjective perception is usually not as sensitive as physiological signals and is easily influenced by external factors.

Design Customized Scenario-Based Assessment Approaches

Most of the current comfort studies of lightweight wearable devices are conducted in controlled laboratory environments. Compared with letting participants experience the device freely in real life, this approach can eliminate the interference of irrelevant factors as much as possible, but it also makes the assessment results susceptible to the influence of experimental tasks. Whether the task design in the comfort assessment approach is in line with the high-frequency use scenarios of the product and whether it can comprehensively reflect the situations that are prone to discomfort is directly related to the validity and practical value of the assessment approach.

Different lightweight wearable devices have different concerns in comfort assessment. First, each product has its specific high-frequency use scenarios. For example, eye-worn wearable devices usually focus on visual tasks, while ear- and wrist-worn wearable devices need to focus on motion scenarios. Second, there are differences in the weighting of comfort dimensions for each product. For example, ear-worn wearables focus more on the tactile dimension of comfort, while eye-worn wearables need to pay extra attention to visual comfort. Finally, there is often a correlation between use scenarios and comfort dimensions. For example, stability is more important in sports scenarios, whereas the pressure perception accumulated during prolonged wear in office scenarios may be more prominent.

CONCLUSION

Comfort is one of the most important factors influencing consumers' purchase intentions for eye-, ear-, and wrist-worn lightweight wearable devices, but the research on comfort assessment for such devices is far from adequate. Based on a review of previous studies, this study appraised the limitations of existing comfort assessment approaches when applied to lightweight wearable devices, and in this regard provided suggestions for the development of subjective assessment tools, the adoption of objective indicators, and experimental designs.

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