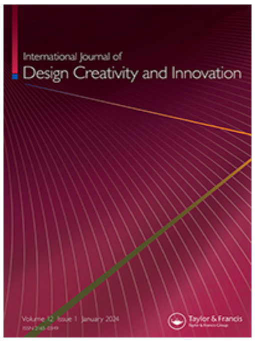

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Human augmentation and its new design perspectives

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ABSTRACT
Along with the growing impact of rapidly advancing technology on human life, interest in improving human abilities has increased. 'Human augmentation' refers to human-computer integration technology, aiming to restore, supplement, or even exceed human potential. As such, human augmentation may be used by anyone, ranging from people who face an impairment or a dangerous situation to healthy people who want to improve their current capabilities or even acquire abilities that are beyond normal human capabilities. This article introduces the field of human augmentation by discussing definitions of human augmentation and related terms. Subsequently, a categorical and dimensional classification of the field is given to structure the domain. Based on our findings from the literature, we propose a framework to support product designers in understanding, navigating, and characterizing the human augmentation product they are designing. This framework was applied in academic practice over three consecutive years, challenging prospective product designers to explore human augmentation. Ultimately, 123 student projects were collected and analyzed with the aim of elaborating on our framework based on concrete design strategies. Future research is set to implement the design strategies in a tool that facilitates idea generation and sparks creativity in the field of human augmentation.

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Human augmentation; product design; wearable technology; human-computer integration; inclusive design

1. Introduction

Human augmentation is an interdisciplinary and relatively new, but rapidly emerging, research field that today studies human-computer integration products designed to improve human abilities. Attempts at human augmentation can be traced back to ancient times, when it usually concerned finding solutions for people with specific needs, for example, replacing a lost body part with an artificial one, such as a leg or arm prosthesis (Alicea, 2018). Due to technological developments, augmentation could be expanded to include improvements that were more advanced. Today, exoskeletons for example, enable someone to lift weights that are extremely heavy, while a jetpack can enable a person to fly (Huber et al., 2018). With the aim of assisting anyone, human augmentation could potentially result in concepts that bridge disability and extra-ability.

Many interdisciplinary pioneers, such as Joseph Licklider (1960), Douglas Engelbart (1962) and William Ross Ashby (1956), have made great advances in the field of human augmentation, and have recognized the potential of technological devices to improve human capabilities. It was only in 2010 that the term 'augmented humanity' was credited to former Google CEO Eric Schmidt, who initially put forward the theory that devices are an extension of a human being's way of thinking (Naughton & Daly, 2020). Since then, numerous developments have occurred, and several articles have extensively reviewed the

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history of human augmentation (Daily et al., 2017; Lee et al., 2018; Pirmagomedov & Koucheryavy, 2021; Raisamo et al., 2019). However, a clear, detailed description of what the term includes and excludes, compared with similar terminology, as well as the fundamental structure or framework of the field, remains to be given. When it comes to 'wearables' or 'tools', for example, it becomes difficult to determine where the borders lie.

To address these gaps, this article presents an introduction to the concept of human augmentation and a thorough outline of the domain and its related terms. We then introduce a framework based on findings in the literature, which we outlined in our previous preliminary literature review (De Boeck & Vaes, 2021). Furthermore, we illustrate how we implemented the framework in the academic context, aiming to provide students with a structural foundation of knowledge on human augmentation. As such, we used it to help them characterize and better understand the type of human augmentation concept they were designing by first considering its location within the framework, and then to broaden their reflection by exploring new directions. Finally, we elaborate on our initial framework with the aim to offer design strategies intended to spark creativity and provide novel design perspectives among prospective product designers regarding human augmentation features. Consequently, our future research will focus on comparing the results of student projects that used the initial framework with those of students using the design strategies for idea generation and creativity, hypothesizing that using the design strategies will result in improved concept generation. Overall, this paper provides valuable insights into the potential of human augmentation as a driver of user empowerment, creativity, and innovation in design.

2. Aim

The aim of this study is to introduce the readers to the emerging research field of human augmentation and its related terminology and to provide a framework for the field as a contribution to the prospective design community. The following research questions were addressed by reviewing relevant literature to date:

(1) How do we define and distinguish human augmentation and its related terms?
(2) What does human augmentation entail and how can it be structured to better understand what it includes and excludes?

Two additional research questions concern our contribution to the design community:

(1) Can a framework be constructed for the field of human augmentation based on our findings in the literature?
(2) What design strategies can be formulated to enhance our understanding of the potential and layered nature of human augmentation – while also inspiring product designers with new insights and sparking their creativity through streamlined guidance during the conceptualization of human augmentation products – which can be implemented and verified in future research?

Accordingly, this paper first provides an extensive understanding of human augmentation as a structural basis of design, which resulted in a visual framework for innovative design perspectives relevant to product designers in this field. We then delve into its practical application, examining how student designers used the framework as a foundation to conceptualize human augmentation products. The paper concludes with the formulation of design strategies based on the analysis of student projects spanning three academic years (2020–2022).

3. Methods

The first method described in this section addresses research questions 1 to 3 and specifies how a literature review was conducted toward the development of a framework. The second method is dedicated to research question 4 and describes how student projects were analyzed to uncover design strategies for human augmentation.

3.1. Literature review towards framework

To identify relevant studies for this review, we used the Web of Science database, complemented by the ScienceDirect and Scopus databases. The search strategy consisted of three consecutive steps. First, a literature search was conducted using the initial keyword search to obtain a preliminary insight into the domain. Second, the literature list was extended through a backward and forward reference search, which involved reviewing references in the articles yielded from the keyword search and reviewing articles that have cited these initial articles (Levy & Ellis, 2006). Finally, this was completed by an additional keyword search.

Accordingly, a first set of keywords was composed for the literature search, which was supplemented with additional keywords (*) after the backward and forward reference search (see Table 1).

We used the keywords from Table 1 and combinations thereof to search the libraries for relevant publications. Initially, the main keywords were searched in each database, within the timespan defined as inclusion criteria ((‘human augmentation’ OR ‘augmented human’ OR ‘augmented humanity’ OR ‘human 2.0’ OR ‘human enhancement’ OR ‘assistive technology’) AND publication date: (2000/01/01 to 2022/12/31)). Additionally, the supporting keywords were used in combination with the main keywords to make the query more related to the search intent (e.g. (‘human augmentation’ OR ‘augmented human’ OR ‘augmented humanity’ OR ‘human 2.0’) AND (‘classification system’ OR ‘subdivision’ OR ‘categorization’ OR ‘structuring’) AND publication date: (2000/01/01 to 2022/12/31)). The following inclusion criteria were applied when screening the titles and abstracts to examine their relevance:

I1. Articles focusing on the subject of human augmentation within the scope of product design, engineering and computer science.
I2. Articles published between 2000 and 2022. This timespan was chosen with the aim of focusing on more recent research, while ensuring the availability of relevant literature. Moreover, the timespan allowed for scoping of the review.

The following criteria were applied to exclude non-relevant articles:

E1. Articles that were not published in English.
E2. Articles that were not peer reviewed.
E3. Articles that referred to human augmentation as an aesthetic surgical procedure, such as dental implants, facial reconstruction, or breast augmentation.
E4. Articles that referred to an augmented human as someone who is able to use augmented reality, virtual reality, or mixed reality effectively, because these do not necessarily contribute to the improvement of human abilities.

Table 1. Main and supporting keywords.

Main keywords	Supporting keywords
Human augmentation, augmented human(ity), human 2.0*	Product development, product design, product engineering, human-computer interaction*
Human enhancement	Classification system, subdivision, categorization, structuring
Assistive technology	Augmented senses*, sensory augmentation*, augmented action*, body augmentation*, physical augmentation*, augmented cognition*, mental augmentation*, cognitive augmentation*

Table 2. Sources with Thomson Reuter's 5-year impact factor or conference CORE rank.

Sources ($n = 56$)					
Journals and magazines	*#*	*IF*	*Conferences*	*#*	*rank*
- Computer (Daily et al., 2017; Vega & Fuks, 2014; Zhang et al., 2017)	3	4.658	- AH: Augmented Human International Conference (Caon et al., 2016; Fan et al., 2014; Kasahara & Rekimoto, 2014; Seigneur, 2011; Xia & Maes, 2013; Xie et al., 2019)	6	N/A
- Futures (Anderson, 2003; Gandy et al., 2016)	2	3.954	- CHI: Conference on Human Factors in Computing Systems (Damian et al., 2015; Eghtebas et al., 2017; Petry et al., 2018)	3	A*
- Pervasive Computing (Kunze et al., 2017; Langheinrich & Davies, 2018)	2	4.196	- SIGGRAPH: Special Interest Group on Computer Graphics (Nabeshima et al., 2019; Obushi et al., 2019)	2	A*
- Frontiers in Human Neuroscience (Cinel et al., 2019; Valeriani et al., 2021)	2	4.111	- MM: Conference on Multimedia (Ranasinghe et al., 2014)	1	A*
- Internet of Things (Pirmagomedov & Koucheryavy, 2021)	1	5.962	- RSJ: International Conference on Intelligent Robots and Systems (Kazerooni, 2005)	1	A
- International Journal of Human-Computer Studies (Raisamo et al., 2019)	1	4.435	- DSCC: Dynamic Systems and Control Conference (Kazerooni, 2008)	1	N/A
- Brain sciences (Valeriani et al., 2019)	1	3.706	- ISMAR: International Symposium on Mixed and Augmented Reality (Damian et al., 2014)	1	A*
- Human-Computer Interaction (Nanayakkara et al., 2013)	1	5.727	- DRS: Design Research Society International Conference (Allen, 2006)	1	B
- Interactions (Fernandes, 2016)	1	N/A	- WeRob: International Symposium on Wearable Robotics and Rehabilitation (Shang et al., 2017)	1	N/A
- The Design Journal (Ramoğlu, 2019)	1	N/A	- IEA: Congress of the International Ergonomics Association (Marti et al., 2019)	1	B
- Journal of Neural Engineering (Nagel et al., 2005)	1	5.671	- UIST: Symposium on User Interface Software and Technology (Leong et al., 2016)	1	A
- Science (Hoy, 2019)	1	59.924	- HCII: International conference on Human-Computer Interactions (Lee et al., 2018)	1	B
- Sensors (Guerrero et al., 2022)	1	4.050	- AltMM: Multimedia Alternate Realities (Woo, 2018)	1	N/A
- Technology and Society Magazine (Oertelt et al., 2017)	1	2.212	- ISTAS: International Symposium on Technology and Society (Pedersen & Duin, 2021; Record et al., 2013)	2	C
- Universal Access in the Information Society (Allen, 2005)	1	2.420	- Living Machines (Bertram et al., 2013)	1	N/A
- Scientific Reports (Schumann & O'Regan, 2017)	1	5.516	- HRI: Conference on Human-Robot Interaction (Weinberg, 2019)	1	N/A
- Science Translational Medicine (Petrini et al., 2019)	1	22.180	- International Conference on Intelligent Environments Workshop (Kymäläinen et al., 2016)	1	B
- Spectrum (Crum, 2019)	1	2.937	PerDis: International Symposium on Pervasive Displays (Tobita, 2017)	1	B
- Artifact (Vita-More, 2008)	1	N/A	***Books and chapters in books***		
- She Ji (Forlano, 2017)	1	N/A	- Assistive Augmentation (Huber et al., 2018)		
- Science Robotics (Mataric, 2017)	1	33.041	- Design Meets Disability (Pullin, 2009)		
- Body and Society (Tamari, 2017)	1	3.173	- Product Stigmaticity: Understanding, Measuring and Managing Product-related Stigma (Vaes, 2014)		
- International Journal of Environmental Research and Public Health (Ho et al., 2022)	1	4.798	- Cybernics: Fusion of Human, Machine and Information Systems. Chapter 7: Augmented Human Technology (Suzuki, 2014)		
- Mechanism and Machine Theory (Chen et al., 2019)	1	4.590	- Connected Objects in Health. Chapter 10: A Step Towards the Augmented Human (Beyala, 2017)		
Journal of Psychology (Lalanne & Lorenceau, 2004)	1	4.450	- Cyber Defence in the Age of AI, Smart Societies and Augmented Humanity. Chapter 2: Augmented Humanity: Data, Privacy and Security (Naughton & Daly, 2020)		

After the screening process, full text articles were analyzed in detail. Accordingly, 97 papers were screened, whereof 63 were included in this literature review. As can be seen in Table 2, the final pool of relevant articles comprised 63 references that were found in journals or magazines (30), conference proceedings (27), or books (6). Finally, based on our literature review, a visualization of our findings in a conceptual framework was pursued as a contribution to the design society.

3.2. Analyzing student projects towards design strategies

The analysis of the student project results was conducted by establishing consensus among the authors, who were also the leading tutors of the practicum and supervised the students throughout the design course. Additionally, the students were also asked to mention how they applied human augmentation in their report. It is important to note that the analysis was not an academic evaluation but focused on evaluating the ideas generated by the students. To ensure objectivity during the analysis and facilitate the identification of relevant design strategies, a systematic approach was adopted by addressing four questions: (i) Was human augmentation applied?, (ii) In which categories are the human augmentation feature(s) situated?, (iii) How did the students apply the feature(s)? and (iv) How can we categorize these applications into concrete design strategies? Some of the design strategies were then combined to eliminate ambiguities through consensual agreement between the tutors. Accordingly, this preliminary yet methodological exploration yielded a non-exhaustive list of design strategies, which will be introduced to students for testing in two subsequent iterations in the future to further refine the tool and its intended purpose. Ultimately, we aim to develop a tool compromising design strategies that were systematically and iteratively formulated, acknowledging that these strategies might not completely be exhaustive due to the inductive research approach. Its primary purpose, accordingly, is to serve as a means for expanding the creative horizons of students.

4. Results

Based on our four research questions, the results were structured into four corresponding subsections. Taking our previous work as a basis (De Boeck & Vaes, 2021), here we elaborate further on the literature review and present a more in-depth and extensive study, supplemented by an analysis of our application of the framework in the academic world.

4.1. Terminology and definitions

The number of publications on human augmentation has increased over time (Guerrero et al., 2022). However, there is still some confusion about what it includes or excludes. When it comes to *tools*, for example, it is unclear where the border lies. Generally, the line is drawn at a product that is so integrated into the user's life that it becomes an extension of them and thus an augmentation. A vacuum cleaner, for example, requires manual control and guidance – depriving the user of their independence – and is only significant to your life when you use it as a tool to clean the floor. An exoskeleton, on the other hand, could become as essential to your life as your ability to walk, making it an example of human augmentation. To clarify, for a product or a technology to be considered an augmentation, it needs to be an extensional and intuitive part of a person's self, whereas a tool requires operation and can never become a part of an individual's self (Alexander et al., 2016).

Another confusing concept is *wearables*, which are smart electronic devices that are worn on the body, where they detect, analyze, and transmit immediate information to the user concerning body signals and environmental data. Because wearables empower the user as extensions that provide augmented information and enable interaction with other smart objects, they can be seen as human augmentation products (Raisamo et al., 2019).

Overall, a good understanding of related terminology is essential to avoid confusion throughout this article. Therefore, this section aims to introduce the reader to the research field of human augmentation and its boundaries with similar, interconnected and even overlapping fields and terms.

First, *assistive technology* refers to rehabilitation technology that allows people with an impairment to participate more fully in society or prolongs the quality of life for the elderly. The US Tech Act of 1988 defined an assistive technology device as 'any item, piece of equipment, or product system, whether acquired commercially off the shelf, modified, or customized, that is used to increase, maintain, or improve functional capabilities of individuals with disabilities' (Code United States, 2020). The US Assistive Technology Act of 2004 essentially uses the same definition as the Tech Act, adding an exception that excludes surgically implanted medical devices, such as cochlear implants. Thus, as a field, assistive technology concerns the development of external products that replace or recover capabilities, depending on specific user needs (Huber et al., 2018). Solutions involving medical interventions that can remedy an impairment, such as a pacemaker or laser eye surgery, are not classified as assistive technology because they typically lead to a complete and, to some extent, permanent recovery from the impairment. Consequently, users may no longer require the ongoing use of assistive technology.

Second, *human augmentation*, or augmented humanity, amplifies and improves the human ability to do work (Mataric, 2017). It refers to technological implementations or extensions that can be used by anyone, including users who face a temporary or permanent impairment, but also healthy users wanting to improve their abilities. Guerrero et al. (2022) most recently proposed the following definition of augmented humanity:

> Augmented humanity is a human-computer integration technology that proposes to improve capacity and productivity by changing or increasing the normal ranges of human function through the restoration or extension of human physical, intellectual and social capabilities.

The abovementioned definition was based on a systematic mapping review and serves as a strong initial foundation. Nevertheless, in this section, we present additional and more elaborate criteria to define the boundaries more clearly and address certain ambiguities. This effort aimed to create a more comprehensive definition of human augmentation, which will be provided after having completed our literature review (see *Section 5. Discussion and conclusion*). To this end, human augmentation:

(i) was defined by Guerrero et al. (2022) as solutions that improve human abilities through human-computer technology. However, this description is not comprehensive enough in our judgment. Examples that are not human-computer technologies, such as prosthetic running blades that may allow the user to run faster than other athletes, analog infrared goggles, or 3D glasses, are not included in their definition. To comprehensively encompass this field, including static, mechanical, and computer-driven technologies, we propose the use of the term 'device-based technology' instead of 'human-computer technology,'

(ii) are technologies that perform as extensions or integrations of the human body by seamlessly adapting to the user's mind, body, and behavior, and thus do not interfere with the user's independence (as opposed to tools). Moreover, these technologies can also be (partly) invasive, such as cochlear implants, pacemakers, and dental braces,

(iii) can be made for anyone, encompassing users who may or may not face an impairment, but pursuits to go beyond stigma-free design and aims for empowerment by making any user feel more capable and self-confident,

(iv) and are situated in specific classification system that will be investigated (see RQ2) throughout this article.

Third, *human enhancement* refers to a similar but broader field than human augmentation, which is why the terms are sometimes used interchangeably. Consequently, the distinction between the two concepts remains unclear and marked by inconsistency to this day. Our primary observation from the literature is that the term 'human augmentation' is predominantly used within the context of product design and human-computer engineering. In contrast, 'human enhancement' extends its application into the medical context, encompassing non-device-based solutions such as medication (e.g., chemical stimulants that can be used to improve intelligence), surgical operations (e.g., organ transplants), or even genetic modification (Anderson, 2003; Daily et al., 2017; De Araujo, 2017;

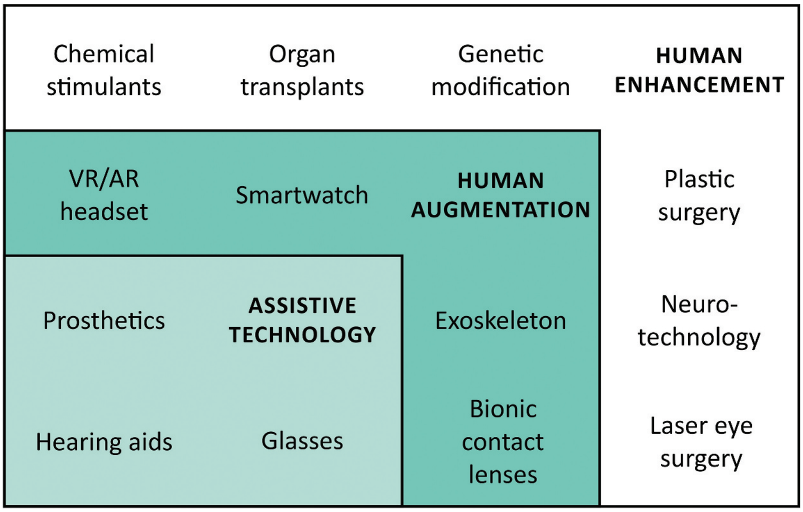

Figure 1. Visualization with examples of human augmentation and related terminology. The colored section falls within the field of product design (i.e., the scope of this article), the non-colored section falls within the medical field.

Pirmagomedov, 2021; Raisamo et al., 2019). Additionally, according to Guerrero et al. (2022), human augmentation does not include medical solutions that can inherently alter human characteristics. Consequently, we adopted the term ‘human augmentation’ over ‘human enhancement’ given its reference to product-based solutions and prevalent usage within the context of product engineering, aligning with the scope of this article. A visualization of the fields discussed can be found in Figure 1, in which the colored section represents the scope of this article. As a general example, a pair of glasses is considered assistive technology, while bionic contact lenses are classified as human augmentation and laser eye surgery as human enhancement.

Finally, two other terms associated with human augmentation are *transhumanism* and *posthumanism*. These are ideological and philosophical movements that speculate on futuristic visions and hypothetical human possibilities, often considering technologies that do not currently exist (Vita-More, 2008). While transhumanism contemplates (the consequences of) re-engineering the human body in various ways to transcend its functional capacity, posthumanism envisions altering human beings so significantly as to no longer represent the human species. In contrast to the pragmatic nature of augmentation and enhancement, transhumanism and posthumanism are speculative approaches and are situated within the realm of philosophy.

4.2. Classification of human augmentation

4.2.1. Dimensional classification

Three dimensions were identified across four scientific articles (see Table 3). This dimensional classification refers to a continuum, where the boundaries are less explicit and along which concepts may be present at various levels. The continuum reflects increasing ability provided to users from the first to the third dimensions.

4.2.1.1. Replicate or restore ability. The first dimension refers to assistive technology and concerns the replication or restoration of a natural human function for someone who does not have it. Replication provides temporary or permanent help to individuals who are suffering from a medical condition, who have experienced a tragic accident, or who face a dangerous or unhealthy situation that may lead them to use augmentation products. As early as in ancient times, people attempted to replicate lost human abilities. Common examples are glasses to restore our vision, prostheses to

Table 3. Different dimensions of human augmentation found in relevant articles.

Dimensions found in the following articles	DIMENSIONS 1. Replicate/restore human ability	2. Supplement human ability	3. Exceed human ability
Vita-More (2008)	The amended body	The extended body	The suspended body
Pirmagomedov and Koucheryavy (2021)	Specific needs	No specific needs	Super-human needs
Daily et al. (2017)	Restore capabilities	Enhance productivity	Improve capabilities
Beyala (2017)	Repaired human	Modify human potential	Expand human potential

replicate our ability to walk – or even run – or hearing aids to improve our hearing. There even is a unique competition called the Cybathlon centered around people with disabilities, in which research teams compete against each other and test the usefulness of assistive technologies in carrying out everyday activities – and thus replicating human abilities (Hoy, 2019). Additionally, restoring a capability may also involve assisting in the recovery of an impairment, such as the use of an orthoptic eyepatch to train a lazy eye and restore sight, or a plaster cast to restore a broken limb. Overall, many researchers, such as Jonathon Allen (2006), Graham Pullin (2009), and Tomoko Tamari (2017), also address the importance of social acceptability and stigmatizing symbolism when designing assistive technology, as it can affect people's willingness to utilize the technology.

4.2.1.2. Supplement ability. The second dimension concerns the extension of our ability to do something. Such technology enables people to do things that are already humanly possible, but better than before. This includes, for example, devices that artificially increase our strength, such as an exoskeleton, or head-up displays that enhance our concentration while driving. A more concrete example is a set of supernumerary arms designed to generate music and improve the musicianship of both people living with and without disabilities (Weinberg, 2019).

4.2.1.3. Exceed ability. Finally, the third dimension concerns augmentation that allows us to do things that we are not able to do in a natural way. Therefore, this dimension is also referred to as that of superhuman abilities, as it can provide the user with capabilities that are super-natural and well beyond the ordinary (Kunze et al., 2017). Examples include products enabling the user to fly, breathe underwater, to see ultraviolet or infrared light, or to smell chemicals currently not detectable by human senses.

In conclusion, anyone can make use of human augmentation products. Therefore, a design approach relevant to this study is inclusive design, also known as universal design, which aims to go beyond the understanding of the users' functional needs. This approach strives to ensure that a maximum number of people can use a product and contends that the single most important component in any system is the user. It takes into account the changes brought about by aging and the variable nature of disability, as well as the technological skills necessary to participate fully in modern society (Vaes, 2014).

4.2.2. Categorical classification

As with the classification into dimensions, different categories of human augmentation were also found in the literature. We found twelve articles from which we derived a classification of human augmentation into four categories (see Table 4).

4.2.2.1. Physical augmentation. This augmentation category aims to improve a human's ability to perform physical actions. One of the earliest and most well-known examples is a prosthetic limb that restores some of the lost capabilities. Today, technological improvements have progressed to such an extent that it is becoming possible to enhance industrial or other kinds of workplace, to

Table 4. Different categories of human augmentation found in relevant articles.

	CATEGORIES			
Categories found in the following articles	1. Physical augmentation	2. Sensory augmentation	3. Cognitive augmentation	4. Social augmentation
Pirmagomedov and Koucheryavy (2021)	Physical augmentation	Advanced sensing	Mental/cognitive augmentation	/
Raisamo et al. (2019)	Augmented action	Augmented senses	Augmented cognition	/
Huber et al. (2018)	/	Sensory substitution	Cognitive augmentation	Interaction techniques
Daily et al. (2017)	Enhanced muscle functioning	Advanced sensory capabilities	Improved brain function	Augmented communication
Lee et al. (2018)	Body augmentation	/	Brain augmentation	Social augmentation
Woo (2018)	Physical abilities	/	Intellectual abilities	Social abilities
Schmidt et al. (2017)	Amplification of physiology	Amplification of perception	Amplification of cognition	/
Buruk et al. (2020)	Enhanced physical skills	Enhanced sensory skills	Enhanced cognitive skills	/
Guerrero et al. (2022)	Augmented physical capabilities	/	Augmented intellectual capacities	Augmented social skills
Gandy et al. (2016)	Improved physically	/	Improved cognitively	Improved socially
Kymäläinen et al. (2016)	Augment the worker's actions	Augment the worker's senses	Augment the worker's cognition	/
Pedersen and Duin (2021)	Physical enhancement	Sensory enhancement	Cognitive enhancement	Emotional enhancement (subset of social augmentation)

enable paralyzed individuals to walk again, or even to augment a human body with a third arm or a sixth finger (Chen et al., 2019; Ho et al., 2022; Kazerooni, 2005, 2008; Kymäläinen et al., 2016; Shang et al., 2017). Additionally, increasing numbers of contemporary physical augmentation devices take into consideration the interaction dynamics of the user and their environment, which means that the appearance and functionality of the product responds to real-time feedback, providing personalized and contextualized adaptations (Suzuki, 2014). Petrini et al. (2019), for example, developed a leg neuro-prosthesis that provided real-time tactile feedback through nerve stimulation, demonstrating that induced sensory feedback can be integrated into a prosthesis to restore functional abilities of the missing leg. Similarly, Leong et al. (2016) developed ProCover, which is a wearable sensing sock that offers noninvasive tactile feedback for individuals wearing lower-limb prosthetics. A less conventional example is that suggested by Xie et al. (2019) and Nabeshima et al. (2019), who both proposed a wearable tail device as an extension of the human body that can provide active balance to the wearer.

4.2.2.2. Sensory augmentation. This category concerns the augmentation of a person's ability to see, hear, smell, taste, or feel. Sensory augmentation can be accomplished through: (i) sensory amplification technology, which makes individual senses more accurate, effective, or powerful. Examples are a hearing aid, reading glasses, night vision goggles, or even 'hearables' that may enable humans to hear sub- or supersonic sounds in the near future (Bertram et al., 2013; Crum, 2019; Pfreundtner et al., 2021). A more concrete academic example of sensory amplification is SpiderVision, which is a wearable device that extends the human field of view so that the user can see what is happening behind their back (Fan et al., 2014). Another method is: (ii) sensory substitution technology, which reassigns sensory information. By allowing characteristics of one sensory modality to be transformed into stimuli for another modality, people with disabilitiesim-pairments or deterioration in sensory abilities can benefit significantly from the technology. The cyborg antenna, for example, is a device that is attachable to the head, which turns colors into audible frequencies. The antenna enables color-blind people, such as the device's inventor, Neil Harbisson, to hear colors (Ramoğlu, 2019). The use of vibrotactile feedback as a replacement for auditory information is also a commonly used manner to enable hearing-impaired people to feel music (Marti et al., 2019; Nanayakkara et al., 2013; Petry et al., 2018). Furthermore, sensory augmentation can also be attained through: (iii) sensory fusion technology, which combines information from different sensory modalities to expand our sensed experiences. For example, the digital application of different colors to a drink and electrical stimulation on the tongue have been explored as feasible taste-improvement methods (Ranasinghe et al., 2014). Another example is the MagniFinger, a fingertip-worn microscopy device that augments the limited abilities of human visual and tactile senses in microscopic environments (Obushi et al., 2019). This latter method of sensory augmentation regarding the integration of information from different sensory modalities is also called 'multimodal interaction' in the field of psychology (Lalanne & Lorenceau, 2004). Finally, Nagel et al. (2005) and Schumann and O'Regan (2017) addressed the possibility of (iv) going beyond – and thus exceeding – our recognized sensory abilities and thus 'obtaining a sixth sense' (Bertram et al., 2013). They proposed a waist belt for tactile feedback and headphones for auditory feedback, respectively, both related to a 'forgotten' sense, as the devices pointed at the magnetic north by means of a built-in compass.

4.2.2.3. Cognitive augmentation. The objective of this category is to augment cognitive abilities and the improvement of the processes of obtaining knowledge (Cinel et al., 2019). Wearables such as smartwatches and activity trackers, for example, can cognitively enrich users by giving them real-time access to information about their personal health. Recent trends in neurosciences have brought multifaceted opportunities for the development of noninvasive cognitive augmentation, including technologies that aim to support memory, attention, awareness of personal and environmental conditions, problem solving, decision-making, and advanced human-computer interaction (Alachouzakis et al., 2018; Bahrainian & Crestani, 2018; Valeriani et al., 2019, 2021; Vega & Fuks, 2014; Xia & Maes, 2013; Yamada et al., 2017). Nevertheless, there is still a long way to go to fully understand the brain, and as long as the brain largely remains a mystery, cognitive augmentation will continue to be just as complicated.

4.2.2.4. Social augmentation. The category of social augmentation aims to improve social skills by supporting empathy, collaboration, communication means, and interaction (Lee et al., 2018). Allen (2005), for example, developed a wearable electronic communication aid for people with communication disabilities. In addition, Damian et al (2014, 2015). proposed a social augmentation concept using a head-mounted display (HMD), with the goal of giving users the ability to continuously monitor their performance as a communicator. Furthermore, Zhang et al. (2017) presented an acoustic signal-based method using the human body as a communication channel to transmit information across different devices. With their proposed method, information such as a business card could be exchanged throughout a handshake. Finally, Kasahara and Rekimoto (2014) developed an interaction system that enables someone to share experiences and receive real-time assistance through first-person-view video streaming. In general, it is notable that virtual, mixed, and augmented realities are often used to artificially augment users' social interactions (Roth et al., 2019; Tobita, 2017). However, there are many other technological tools, means and design approaches to attain social augmentation. Overall, despite its significant future value, augmentation of social abilities has not been as thoroughly studied as the other categories mentioned above (Lee et al., 2018).

Generally, when developing human augmentation products, hardware is often the limiting factor, according to Pranav Mistry (Langheinrich & Davies, 2018). Progress is somewhat constrained compared to software, where advancements in machine learning, AI, and computer-vision algorithms are led by a larger pool of experts, currently influencing necessary hardware improvements.

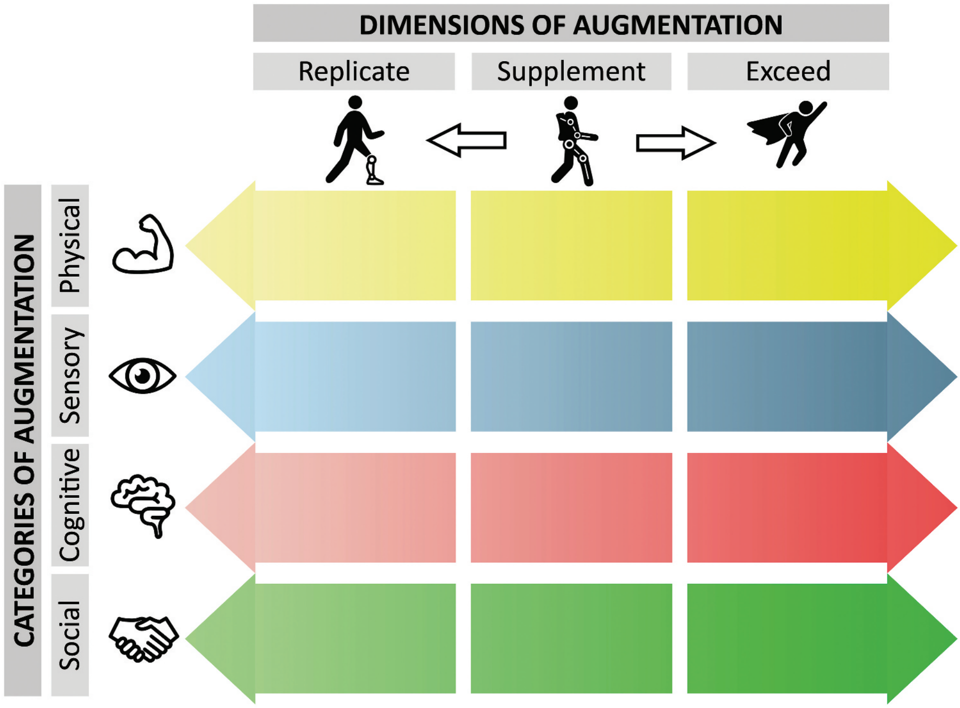

Figure 2. Visual framework of human augmentation possibilities.

4.3. Framework of human augmentation classifications

In Figure 2, we propose a framework visualizing both classifications, which could prompt designers to reflect more broadly on the potentials of their product by suggesting innovative directions (De Boeck & Vaes, 2021). For example, a hearing-aid designer who was initially solely focused on replicating the wearers' ability to hear could utilize the framework to explore novel features, such as filtering out white noise (i.e., exceeding sensory augmentation), or enabling visual feedback on the opponent's audibility (i.e., supplementing social augmentation).

4.4. Applying human augmentation in academic practice towards design strategies

After the literature review and its translation into the framework, we implemented the knowledge gained in the context of academic practice for exploratory verification. During a university course on Inclusive Design in Product Development, third-year Bachelor's students of the Faculty of Design Sciences at the University of Antwerp were introduced to the field of human augmentation and its theoretical underpinnings, illustrated with relevant examples from the contemporary design world. As a design assignment, they were then challenged to develop a human augmentation concept and to elaborate on this initial concept using the framework. Of course, the intention was not to conceptualize a product with many additional features, rather the students were challenged to think about the enriching potential within the world of human augmentation. During consultation sessions, they were encouraged to consider a movement toward the right side of the dimension spectrum to provide supplementary or even excess empowerment to their users and to explore additional categorical features. Accordingly, the students explored how to design for the 'augmented human' while focusing on the impact of their product on the user and less on technological elaboration. In total, *123 student projects* were completed and submitted over three consecutive years (44 projects in 2020, 41 projects in 2021, and 38 projects in 2022).

4.4.1. General observations on how students applied the framework

Each year, we observed that students could conceptualize a human augmentation idea without difficulty. These initial ideas generally concerned a functionality that belonged to one category and one dimension, with *physical augmentation* the most common category and *replicating abilities* as the most common dimension (see Table 5). When encouraging the students to use the framework, it became apparent during consultation sessions that distinguishing between the dimensions was challenging because the boundaries along the dimensional continuum were not explicit. The categorical classification, however, proved to be more useful, as it provided guidance on possible aspects they could augment. Moreover, *social augmentation* was found to offer a lot of uncharted potential, which encouraged them to pursue concepts involving innovative social features. At the same time, we discovered that *cognitive augmentation*, which was the least common category applied by the students each year, did not provide many innovative opportunities from the design perspective and that it should be explored from the neuroscience point of view due to its intrinsic complexity.

Despite having provided the students with the framework as a structural foundation for their design projects, three of the four categories (sensory, cognitive, and social) and two of the three dimensions (supplement and exceed) remained underexplored. Therefore, our analysis aimed to provide more guidance in idea generation and to show the potentials of human augmentation.

4.4.2. Analyzing student projects towards design strategies

All 123 projects were analyzed to evaluate how the students applied human augmentation, with the aim to further elaborate our preliminary framework with the addition of specific strategies. Thus, categorical classification was not only used to describe what was being augmented but also how the students approached their project, while the dimensional classification referred to the degree to which a specific feature would augment its user. Moreover, due to unclear boundaries of the dimensional continuum, the dimensional classification presented ambiguity. Therefore, the analysis was performed by examining which categories were applied and how they were implemented in each project. We then translated our insights into specific design strategies for each category.

The analysis resulted in a preliminary list comprising 23 design strategies for applying human augmentation, each assigned a code for easy reference throughout this article. The list is presented in Figure 3 and is non-exhaustive but may prompt idea generation for future designers seeking to apply human augmentation strategies in their work. In future research, we will aim to verify this claim.

Table 5. Distribution of categories and dimensions (2020–2022).

	2020 (44 projects)			2021 (41 projects)			2022 (38 projects)		
	Main function	Extra function	Extra function	Main function	Extra function	Extra function	Main function	Extra function	Extra function
Categories:									
Physical	**24**	0	1	**24**	0	0	**15**	0	0
Sensory	9	4	0	11	2	1	10	1	1
Cognitive	3	0	3	2	5	0	5	2	3
Social	8	7	0	2	11	4	8	27	0
Dimensions:									
Replicate	**30**	5	1	**30**	7	1	**25**	7	2
Supplement	14	5	3	8	11	4	9	19	1
Exceed	0	1	0	1	0	0	4	4	1

Design strategies to apply physical augmentation							
Design strategy	A1. Amplifying force and movement	A2. Improving mobility	A3. Improving steadiness	A4. Correcting posture	A5. Protecting/ supporting body parts	A6. Improving dexterity and agility	A7. Obtaining a healthy state of internal conditions
Student example	Motorized knee brace	Walking stick	Wrist brace preventing tremors	Posture-correcting back brace	Redesign of arm cast	Swimming prosthesis	Oxygen mask
#	5	6	3	12	14	6	18

Design strategies to apply sensory augmentation			
Design strategy	B1. Sensory amplification or reduction: making senses more effective	B2. Sensory substitution: reassigning sensory information	B3. Sensory fusion: formulating new sensory modalities that expand our senses
Student example	Cochlear implant	Glove that translates sign language into written feedback	Wearable translating colors into sounds
#	21	14	4

Design strategies to apply cognitive augmentation						
Design strategy	C1. Enabling human-computer interaction	C2. Improving productivity	C3. Enabling navigation	C4. Creating personal health awareness	C5. Enabling cognitive verification	C6. Learning new skills or habits
Student example	Smartwatch that interacts with devices through hand gestures	Brain monitor that alerts when to take a break	Walking cane that projects directions	Hearables monitoring stress level	Headset verifying an image with AI	Customizable sport crutches
#	2	5	5	7	1	3

Design strategies to apply social augmentation							
Design strategy	D1. Sharing social activities	D2. Sharing experiences	D3. Broadcasting about wearer/ environment	D4. Supporting communication/ interaction	D5. Facilitating making contact	D6. Informing you do not want contact	D7. Facilitating asking for help
Student example	Inviting friends to play along	Sharing music	Color changing mask	Throat mic with adjustable sound levels	Inviting friends to play along	Headphones signaling contact status	Sending for help when fallen
#	7	4	17	22	5	5	7

Figure 3. Design strategies for applying human augmentation, divided into the four categories.

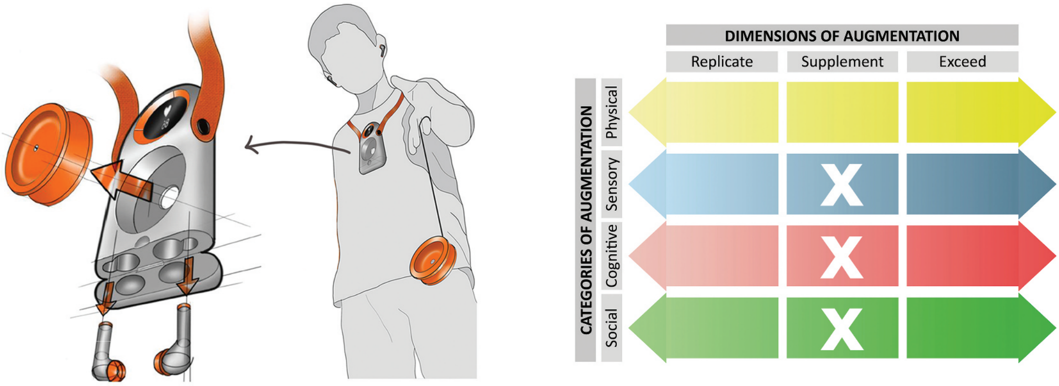

Figure 4. 'Hangmate' – a wearable for children with autism. By students Thomas De Clerck and Toon Claes (2020).

4.4.3. Educational examples

From our pool of 123 projects, a small selection of inspirational examples will be discussed here to illustrate: (i) how the students used the framework to be inspired with new insights and opportunities within their project and (ii) how we translated the features they implemented into design strategies for our analysis.

The first human augmentation example we discuss is a wearable for children with autism (see Figure 4), featuring emotion buttons for social augmentation (D3, Figure 3) and detachable noise-canceling earbuds for sensory augmentation (B1, Figure 3). Additionally, the wearable includes a yo-yo as a playful distraction when feeling overwhelmed. This feature contributes to a more comfortable cognitive state (C6, Figure 3) and encourages social interaction (D4, Figure 3) by allowing other children to join in, fostering a sense of ease and companionship.

The second example involves innovative noise-canceling earpieces (see Figure 5). When the feathers are down, bystanders are informed that the noise cancellation is disabled. When the feathers are up, they produce ambient light such that bystanders are informed that the wearer has activated the 'party mode' and that the noise cancellation is activated (B1, Figure 3). As such, the wearer wants to convey that they are not open to dialogue (D2, Figure 3), additionally resulting in party vibes for the environment (D3, Figure 3).

A third example is a swimwear set equipped with sensors designed for visually impaired individuals (see Figure 6). The swimsuit detects the swim line and nearby swimmers while

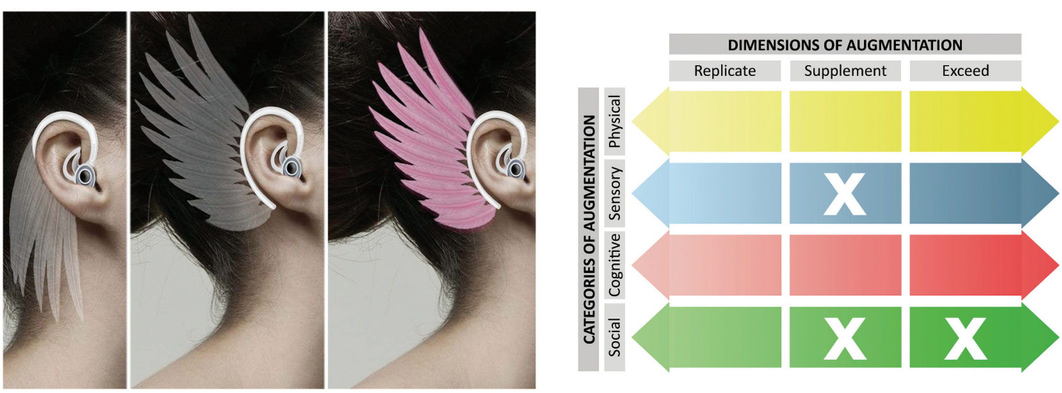

Figure 5. 'Sweven' – noise-canceling earpieces providing bystanders with feedback. By students Sam Warmer and Kobe Baudewijns (2021).

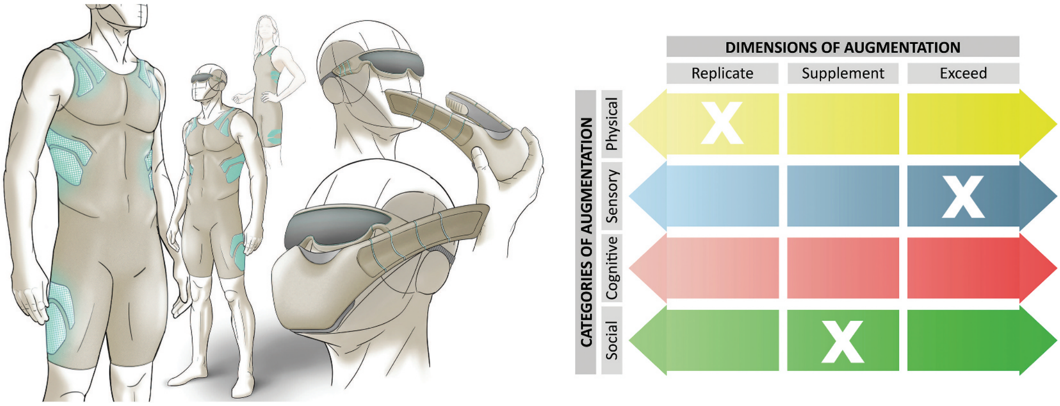

Figure 6. 'Hydraptic' – a swimwear set for guidance through haptic feedback. By students Louise Berckmans and Simon Bracquené (2022).

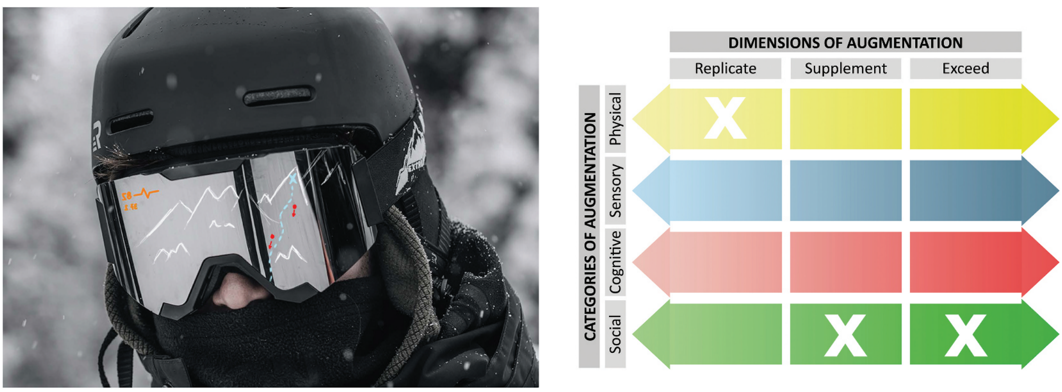

Figure 7. 'Venture – a smart AR helmet for extreme sports fanatics. By students Jelmer Vervoort and Anthon Van Dyck (2022).

providing haptic feedback to its user, making it a form of physical augmentation as it replicates the ability to swim safely (A2, Figure 3). Additionally, the sensors act as an extension of vision and can even detect swimmers who are behind the user, enhancing sensory capabilities beyond normal vision (B2, Figure 3). The set also includes light effects to broadcast the wearer's direction, serving as social augmentation (D3, Figure 3) and offering visually impaired individuals the support they need for safe and enjoyable swimming.

The final example is a helmet with integrated AR goggles and a headset for extreme sports, such as off-piste skiing (see Figure 7). The helmet protects the head from potential injuries (A5, Figure 3), replicating the natural ability to stay safe in dangerous situations. Additionally, the helmet facilitates team communication (D4, Figure 3) and allows the members to track each other through the AR goggles (D3, Figure 3). As such, the members can alert one another to acute danger, enabling the team to operate more safely as a cohesive unit. In case of an injury, the team can provide immediate assistance (D7, Figure 3), demonstrating the potential for socially augmenting a team as a whole.

5. Discussion and conclusion

This paper has introduced readers to the interdisciplinary field of human augmentation and provided a contribution to its design community by addressing four research questions. The first research question resulted in a comprehensive understanding of the field and related terminology to build a structural foundation, culminating in a visual representation for greater clarity. Given the persistent ambiguity surrounding the concept of human augmentation and its distinction from related terms, we hereby propose a refined definition derived from our literature review:

> Human augmentation refers to the development of **device-based technologies** that aim to **improve human abilities** as an **extension** or **integration** of the human body by **replicating**, **supplementing**, or **exceeding** the **physical**, **sensory**, **cognitive**, and **social capabilities** of its user. Human augmentation is primarily used within the context of **product design** and **engineering**, striving to **go beyond design for (dis)ability**.

The second research question yielded a classification of the field into four categories (physical, sensory, cognitive, and social augmentation) and three dimensions (replicating, supplementing, and exceeding human ability) derived from various articles. Subsequently, the third research question resulted in the construction of a visual framework representing these categories and dimensions, which could enable product designers to better characterize and conceptualize human augmentation products. The fourth and final research question aimed to explore the potential of the framework to spark the creativity of prospective product designers. As such, students were challenged to conceptualize a human augmentation proposal and expand on their initial concept using the framework. A comprehensive analysis of 123 student projects spanning three consecutive academic years (2020–2022) was conducted to elaborate on our framework. This effort resulted in a preliminary list of 23 concrete design strategies intended to improve understanding and idea generation on human augmentation among product designers.

In addition to our research, we wish to emphasize the importance of addressing the ethical issues that human augmentation may entail, a topic that has been highlighted in many articles due to its possible effects on humans and society as a whole (Caon et al., 2016; Forlano, 2017; Naughton & Daly, 2020; Oertelt et al., 2017; Record et al., 2013). Such powerful technology could facilitate our lives in the future, but it could also end in an unmanageable and frightening nightmare. With the current ubiquitousness of sensors, connected devices, big data, and artificial intelligence (AI), the privacy of individuals could be breached at unparalleled levels. Raisamo et al. (2019) even referred to George Orwell's novel, *1984*, to alert us about the worst-case scenario of mass surveillance, societal control or even abuse by higher authorities. Furthermore, it could also have other social consequences, such as encouraging further inequality and detraction of our personhood or social unacceptance – even if it is empowering to its user (Eghtebas et al., 2017). However, as with most ethical issues, this is not a black-or-white matter. The emergence of human augmentation can also lead to global improvements in health, quality of life, and productivity. Moreover, despite criticism that human alienation is a potential side effect of technological development, social augmentation may intend to foster social bonding and connection between people, showcasing the significant promise within this category. Overall, when properly integrated into our society, human augmentation can improve the lives of many individuals (Fernandes, 2016). Nonetheless, its evolution needs to be closely monitored to ensure ethical development.

Finally, we conclude this article by outlining our forthcoming research steps, which will focus on translating the identified design strategies from this study into a practical tool. This tool will aim to improve comprehension of human augmentation, facilitate idea generation, and stimulate creativity among product designers. Additionally, it will prompt designers to reflect on the potential ethical issues often discussed in the literature concerning human augmentation. This integrated approach aligns with our commitment to advancing knowledge in the field and contributing to the responsible development of human augmentation.

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