

Wearable technology in the operating room: a systematic review

Lauren Kolodzey,¹ Peter D Grantcharov,¹ Homero Rivas,² Marlies P Schijven,³ Teodor P Grantcharov,⁴ on behalf of the Wearable Technology in Healthcare Society

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¹Li Ka Shing Knowledge Institute, St. Michael's Hospital, Toronto, Ontario, Canada

²Division of Bariatric and Minimally Invasive Surgery, Stanford Medical Center, Stanford, California, USA

³Department of Surgery, Academic Medical Centre, Amsterdam, The Netherlands

⁴Division of General Surgery, St. Michael's Hospital, Toronto, Ontario, Canada

Correspondence to

Lauren Kolodzey, Surgical Education and Innovation Research Group, St. Michael's Hospital—Li Ka Shing Knowledge Institute, 883.21, 209 Victoria Street, Toronto, ON M5B 1T8, Canada; lauren.kolodzey@mail.utoronto.ca

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ABSTRACT

Wearable technology is an emerging manifestation of consumer electronics that has the potential to revolutionise healthcare. The novel hands-free design and clinically relevant functionalities of various wearable devices hold significant promise for surgery, but the breadth and quality of evidence supporting clinical implementation in the operating room remains unclear. The objective of this article is to provide an objective overview of the available literature regarding the use of wearable technology in surgery, both in clinical and simulated experimental settings. A systematic review examining the use of wearable technology in surgery was conducted in accordance with the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) guidelines using the MEDLINE and Web of Science databases from inception through 15 January 2016. Three authors independently screened the titles and abstracts of the retrieved articles and those that satisfied the defined inclusion criteria were selected for a full-text review. A total of 87 publications were included in this review. These articles predominantly described the use of Google Glass, GoPro or customised head-mounted displays (HMDs) in a wide range of intraoperative clinical settings. The included articles were categorised based on the highlighted areas of clinical impact, with the majority (56) discussing various applications for enhancing intraoperative safety and efficiency. Almost all articles cited technological limitations and privacy concerns as serious barriers to the implementation of wearable technology in the operating room. Evidence in the available literature regarding the use of wearable technology in the operating room shows promise, but high-quality clinical trials are needed to fully understand their clinical impact. Further, it will be essential to address existing technological limitations, develop healthcare-specific applications, and integrate privacy-protecting safeguards before it may be feasible for wearable devices to seamlessly integrate into the operative environment.

INTRODUCTION

Over the past decade, the landscape of consumer electronics has experienced a dramatic evolution culminating in the emergence of wearable technology. Typically referring to electronic devices with sensing and computational capabilities that are worn by or attached to the body,¹ wearable technology has the potential to be a disruptive force in healthcare, particularly in surgery. With the hands-free form factor of devices enabling telecommunication and point-of-view video recording in the operative environment with minimal hindrance to user activity, the introduction of wearable technology in surgery may have a tremendous transformative impact on surgical education, intraoperative documentation and direct patient care.^{2–4}

While interest among medical professionals surrounding consumer wearable devices has precipitated widespread discussion of potential applications in surgery, evidence to support their utility in this context is often anecdotal.⁵ As wearable technology becomes increasingly pervasive, it is essential that decisions regarding their integration into clinical practice be based on critical analyses of empirical evidence rather than novelty.

In this systematic review, our objective was to present an overview of the available literature regarding the use of wearable devices in surgery, both in clinical and simulated settings, as well as to objectively discuss factors affecting their integration into standard clinical practice.

METHODS

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) guidelines. Electronic searches were performed

across the MEDLINE and Web of Science databases from inception through 15 January 2016.

For the purpose of this review, wearable technology was broadly defined as any device that is worn by or attached to the body and is capable of providing the user with usable data. The systematic search strategy was developed by two authors (PDG and TPG) according to this definition and was executed with the assistance of a research librarian at the Health Sciences Library of St. Michael's Hospital. The following free-text search terms were used: 'wearable technology', 'surgery', 'surgeon', 'telemedicine', 'augmented reality', 'head-up display', 'head-mounted display', 'Google Glass', 'GoPro', 'smartglasses', 'smartgoggles', 'wearable computing', 'surgical procedures' and 'operative', combined so as to capture papers featuring both specific and generic terminology. Appropriate variations of these search terms were also used to account for alternate spellings and plurals, and search results were restricted to the English language. The full systematic search strategy is provided in online supplementary appendix 1.

Inclusion in this systematic review was limited to publications that evaluated or discussed the application of a wearable technology in a surgical context, irrespective of the intended user. Non-clinical studies that evaluated a wearable technology with the intention of eventual implementation in a surgical setting were considered to satisfy these criteria. Titles and abstracts of studies retrieved through the database search were screened independently by two authors (LK and PDG), and one author (LK) performed a full-text review of all relevant publications. References of the selected full-text articles were further analysed for additional relevant publications.

Data extracted from the included publications were publication type, clinical setting, the wearable device assessed, methods and key results. Synthesis of the results was facilitated by subsequently grouping the publications based on common themes within each category of extracted data.

RESULTS

A total of 614 publications identified by the database search were subjected to title and abstract screening, and 108 were selected for a full-text review. Of these, 28 were excluded for failing to satisfy the eligibility criteria. An additional seven publications identified during the manual bibliographic search were included following a full-text review. Thus, 87 publications ultimately fulfilled the inclusion criteria for this review (figure 1). These publications represented a range of article types (table 1), presenting wearable technology applications for various clinician roles in a variety of relevant specialties (table 2). Of the articles describing the use of wearables by surgical staff, 20 specifically concerned applications during minimally invasive surgery (MIS).

The included publications were also categorised into four groups based on the wearable device featured: (1) GoPro, (2) Google Glass, (3) head-mounted display (HMD) and (4) other; and four groups based on the discussed areas of clinical impact: (1) information management, (2) communication, (3) education, and (4) safety and efficiency.

Wearable devices

Google glass

Thirty-four articles concerned the use of Google Glass (Google, Mountain View, California, USA).^{1-3 5-35} Worn in the same manner as a conventional pair of glasses, Google Glass consists of a wire frame integrated with a computerised central processing unit, a 5MP camera for point-of-view picture and video capture, and a small head-mounted prism display that sits above the right eye.^{2 7} The device is capable of wireless connectivity and is equipped with various sensors to enable control via voice command, touch, blinking and head movement.^{2 3 16} Two publications^{30 31} featured customised versions of Google Glass, modified through the integration of third-party software.

Fifteen of the 34 articles (44%) featuring the use of Google Glass were primary research articles;^{2 5 8 10 11 15 16 19 21 26 28 31 32 35 36} of these, 12 described either exploratory studies or 'proof-of-concept' case studies in clinical settings. In general, all of these studies concluded that Google Glass has the potential to enhance various aspects of surgery, but the majority highlighted functional limitations (eg, limited battery life, insufficient resolution and rudimentary voice control), usability issues (eg, incompatibility with surgical loupes, mismatch between the user's natural line of sight and the position of the display) and privacy concerns as significant barriers to practical clinical implementation.

GoPro

Nine publications featured various iterations of the GoPro camera system (GoPro, San Mateo, California, USA), including the GoPro HERO3, HERO3 Silver, HERO3 Black, HERO4 Black and the stereoscopic 3D HERO system.^{34 35 37-43} The GoPro series of cameras are commercially available 'action' cameras typically used for extreme sport photography.^{39 43} They consist of a high-definition (HD) camera encased in a compact frame that can be strapped to the head or body of the user.⁴²

Five of the nine articles (56%) were primary clinical research articles that evaluated various GoPro devices.^{35 38 39 42 43} All of these studies found that the technical specifications of the models tested could be adjusted to optimise the quality of picture and video capture such that fine details within the surgical field could be visualised. However, the lack of an

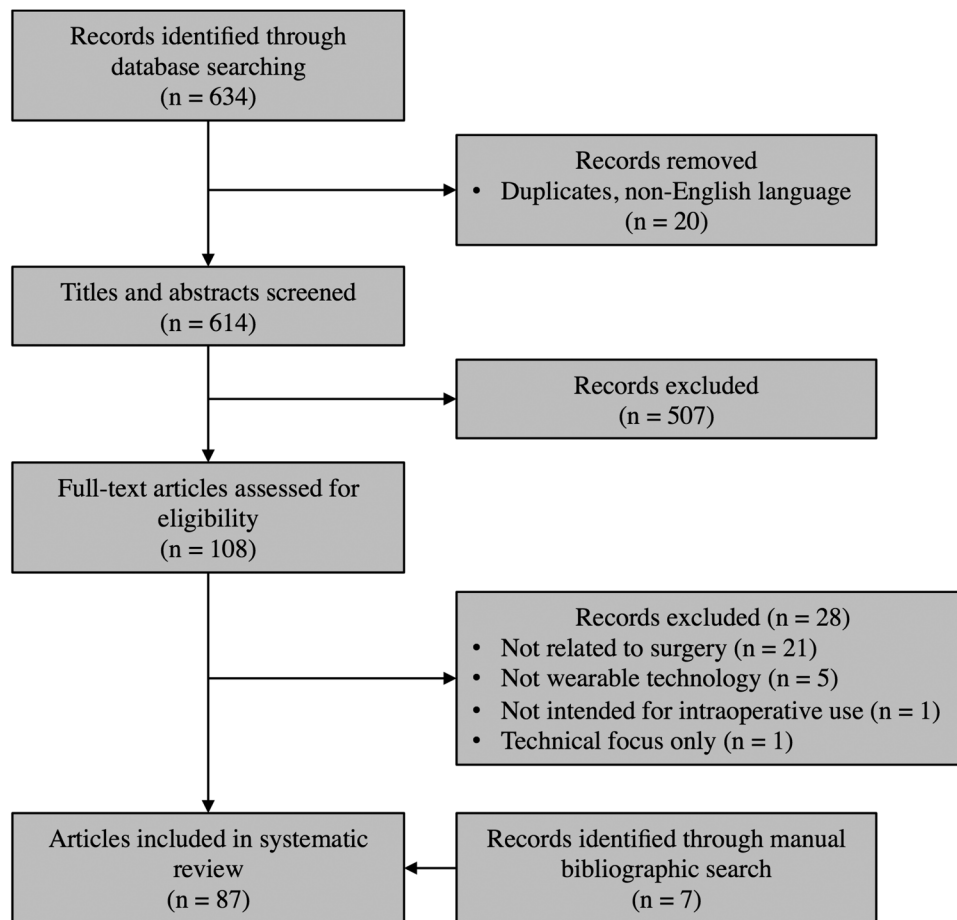


Figure 1 Flow diagram depicting a systematic review strategy.

Table 1 Distribution of the included publications across article types

Publication type	Number of studies
Primary research article	
Clinical study	26
Clinical case study	10
Clinical simulation study	9
Animal model study	6
Technical study	9
Secondary research article (review)	5
Analysis	5
Editorial/commentary	6
Letter to the editor	11
Total	87

integrated screen and the weight of the device were noted as clinically significant usability issues.

Head-mounted display

A total of 45 publications described the use of see-through HMDs produced by a variety of manufacturers, including Sony Corporation, eMagin, Vista Medical Technologies, Microvision and others.^{32 44–87} The term ‘HMD’ refers to a class of head-worn

displays capable of superimposing computer-generated imagery over the user’s field of view.⁶¹ Generally, there are two classes of see-through HMDs: optical and video.⁴ Optical see-through HMDs allow the user to view the real world through a semitransparent mirror, thereby enabling the superimposition of electronic text or images over the user’s natural view, while video see-through HMDs feature non-transparent screens that instead display a video feed of a real-world scene, captured with an external camera, in front of the user’s eyes.⁸⁸ The use of video HMDs was described in all 20 articles pertaining to MIS where HMDs provided users with an individualised endoscopic display.^{44 49 51–54 56–58 64 65 69 72 80 81 83–87}

Thirty-three of the 45 articles (73%) describing the use of HMDs were primary research articles, 19 of which were exploratory studies carried out in clinical settings.^{47 49 51 52 55–58 65 66 69 71 80 81 83–87} Device design and methodology varied significantly across these studies, but the results overall demonstrated the feasibility of HMDs in the various specified clinical environments. Notably, device ergonomics (eg, weight) and usability issues (eg, wire connectivity, inattention blindness) were generally cited as hindering factors to practical clinical implementation, and one clinical study⁸⁵ reported negative physical side effects among

Table 2 Distribution of the included papers across clinical specialties

Clinical domain	Number of studies
General surgery	22
Surgical specialties	
Urology	12
Orthopaedic	6
Dermatology	5
Interventional radiology	5
Neurosurgery	5
Plastic	5
Cardiology	3
Ophthalmology	3
Maxillofacial	2
Oncology	2
Fetal	1
Hand	1
Limb preservation	1
Otolaryngology	1
Paediatric	1
Periodontic	1
Spine	1
Anaesthesia	10
Total	87

HMD users, including eye fatigue, dizziness and headache.

Other

An additional three wearable devices were discussed in three separate articles; these were the FitBit (Fitbit, San Francisco, California, USA), a wrist-worn personal activity monitor that collects user movement data using an imbedded accelerometer,³³ a customised HMD with an integrated iGen Night Vision Viewer (First Texas Products, El Paso, Texas, USA) for fluorescence visualisation in tumour resection surgery,⁸⁹ and a hands-free headset for interpersonal communication in a dermasurgery clinic.⁹⁰

Clinical applications

Communication

A total of 21 articles evaluated or discussed the ability of wearable devices, especially Google Glass, to facilitate valuable communication within an operative setting. Most frequently discussed was the potential for teleconferencing, which involves providing a live video feed of an ongoing surgical procedure to remote observers using the video-streaming functionality of a wearable device, or teleconsultation, whereby clinicians in geographically distinct locations consult with one another via video-streaming software. Hamann *et al*¹⁵ studied the use of Google Glass for videoconferencing and teleconsultation in dermatological surgery, where Google Glass was used to send a live video feed of a recent excision site to a

team of surgeons at a distant location who were then able to participate in the clinical decision-making process.

Education

Educational applications of wearable technology were featured in 25 articles. Wearable devices with point-of-view recording and video-streaming capabilities were predominantly identified as potential educational tools for training surgical residents via telemonitoring, as demonstrated by Rahimy and Garg²⁶ in the context of ophthalmological surgery. In this clinical study, an ophthalmologist wore Google Glass while performing scleral buckling surgery, a procedure with a small operative field that is not conducive to conventional trainee instruction, thereby allowing trainees to visualise a video stream of the primary surgeon's field of view on a monitor with real-time narration. Warrian *et al*⁴² additionally highlighted the utility of GoPro devices in the context of surgical education by using both head-mounted and chest-mounted GoPro cameras to record the surgeon's manner of handling the surgical instrumentation and the corresponding instrument movements within the surgical field during oculoplastic surgery.

Safety and efficiency

A total of 56 articles featured applications of wearable technology that have the potential to impact intraoperative safety and/or efficiency. Devices in this category were diverse, including a see-through HMD for monitoring physiological patient data that enables anaesthesiologists to limit time spent looking away from the patient,⁷⁰ and HMDs with fluorescence visualisation capability for identifying margins in tumour resection surgery.^{62 63} Efficiency-enhancing applications were equally broad, encompassing the use of Google Glass to display and facilitate the completion of surgical checklists,^{3 22 25 29} and the use of HMDs to provide surgeons performing minimally invasive procedures with individual endoscopic displays.

Information management

Finally, 20 articles discussed the ability for wearable devices to manage textual, pictorial and numerical information intraoperatively. Associated applications included photodocumentation via picture and video capture, voice-initiated intraoperative dictation, and the collection of personal movement data to facilitate the assessment of specific surgical skills.³³

A thematic categorisation of the potential clinical applications of wearable devices, as discussed in the articles included in this review, is given in [table 3](#).

DISCUSSION

Technological advancements in recent years have given rise to the imminent possibility of pervasive wearable technology in surgery. In this review, we comprehensively summarised the current literature

Table 3 A summary of the clinical applications of wearable technology discussed in the included articles

Category	Clinical applications	Articles
Communication	<ul style="list-style-type: none"> ▶ Teleconferencing ▶ Teleconsultation 	2 5 7 8 11 15–19 21 23–25 27 35 40 68 84 89 90
Education	<ul style="list-style-type: none"> ▶ Telemonitoring ▶ Self-evaluation through review of recorded intraoperative data (pictures, video, movement data) 	2 5–9 11 14 18 21 24–26 28 29 33–38 67 78 84
Safety and efficiency	<ul style="list-style-type: none"> ▶ Anaesthesia monitoring ▶ Surgical navigation/image guidance ▶ Augmented reality ▶ Facilitation of surgical checklists ▶ Step-by-step surgical procedure guidance in real time for scrub nurses ▶ Improved surgical performance/efficiency (speed, accuracy) ▶ Improved intraoperative workflows/ergonomics 	1–3 5 9 10 12 17 22 25 27 29 31–33 36 44–51 53–63 65–77 80 82 83 85–87 89 90
Information management	<ul style="list-style-type: none"> ▶ Photodocumentation ▶ Video recordings of surgical procedures ▶ Video recordings of patient consultations ▶ Voice recorded notes ▶ Access to preoperative images (eg, MRI) 	3 5–7 9 15–18 20 23 27 34 38–43 49

regarding the use of wearable technology in the operating room with a view to clarifying the evidence supporting the integration of wearable technology into clinical practice.

Among the most significant findings of this review was the lack of high-quality evidence supporting the use of wearable technology in surgical settings. That the majority (69%) of the articles included in this review were primary research articles is promising, yet only 30% of the described studies were carried out in clinical settings, and none of these were formal randomised controlled trials. While the prevalence of observational methodologies may be attributed to the prerequisite to establish ‘proof-of-concept’ or the early prototypical nature of many of the devices studied, it is essential that their impact on critical intraoperative parameters be explored through well-designed clinical trials before these devices can be recommended for exclusive implementation in standard surgical practice.

This review highlighted the use of a variety of wearable devices in operative settings; those featured most predominantly included HMDs, Google Glass and GoPro cameras. Despite the general lack of high-quality studies surrounding these devices, the information presented sufficiently illustrated the relative strengths of each in addition to potential clinical applications. Strengths of Google Glass included its lightweight construction, user-friendly interface and potential for hands-free control; GoPro devices were universally praised for their powerful HD cameras capable of capturing precise anatomical detail; and HMDs were described as the first practical apparatuses to bring augmented reality to the operating room.²

Certain HMDs were found to be particularly useful in the context of MIS. By providing surgeons with an individualised display of the endoscopic video feed, an HMD frees the user from gazing at a stationary monitor, thereby allowing the user to adopt a more natural and ergonomically favourable position throughout the case.⁶⁹ Furthermore, most HMDs are semi-immersive, meaning they allow users to have a direct view of the patient below the electronic display; by aligning the direct and indirect views in this way, HMDs may also eliminate the inefficiency and risk of technical error associated with looking back and forth between the endoscopic monitor and the operative field.⁴⁹

In categorising the included articles based on area of clinical impact, we found that applications of wearable technology predominantly focused on improving the safety and efficiency of intraoperative processes. The associated applications were novel, wide-ranging and designed for use by a variety of care providers, thereby reflecting the interconnected relationship between intraoperative safety and the entire healthcare team. Furthermore, the applications presented suggest that wearable devices may be able to resolve certain human factors that negatively influence performance and safety in the OR. For example, HMDs designed for intraoperative anaesthesia monitoring maintain a display of patient variables within the physician’s field of view to mitigate attentional conflicts associated with patient care tasks and the distracting operative environment.⁷⁵ Indeed, wearable devices may have an important role to play as the need for quality and safety improvement in healthcare increasingly becomes a driving force for innovation.

Beyond enhancing intraoperative safety and efficiency, the clinical implementation of wearable devices, especially Google Glass, may have a particularly significant impact on surgical education. By circumventing logistical challenges associated with conventional surgical observation, wearable devices with point-of-view video recording and live-streaming applications have the potential to bring surgical demonstrations at any given location to a global audience. Allowing trainees themselves to wear video-recording devices while operating independently may also be beneficial, as this could enable their superiors to remotely supervise in real time or to accurately assess surgical skill through video review, which would provide significantly more detail surrounding the case compared with retrospective reporting alone.²⁸

Despite the numerous potential clinical applications of wearable devices, various functional limitations may hinder implementation. Unrestricted freedom of motion gave battery-powered wearables a distinct advantage over their wire-connected counterparts, but poor battery life was repeatedly cited as a serious limitation to device usability; when subjected to the heavy usage of continuous video streaming, Google Glass had a reported battery life of 30–40 min,^{5 10} while GoPro devices required charging after 90 min of continuous recording.^{39 43} Since these devices were originally developed for the consumer market,^{1 2} it is not surprising that their designs and capabilities have not been optimised for medical applications. For wearables to achieve practical intraoperative implementation, improved battery technology will be critical, as will be device-specific modifications, such as improved camera resolution and a more accurate alignment between the field of view of head-worn cameras and a surgeon user's downward line of sight.^{16 36} Device design also has important implications for intraoperative safety; poorly designed head-worn displays have the potential to cause inattention blindness, described as an impeded ability to focus on and detect events in the surrounding environment.^{10 60 75 76} To successfully expand the use of wearable devices to the operating room, user-centred design will be imperative for optimising usability, promoting clinical uptake and, most importantly, protecting patient safety.

One final concern associated with wearable devices is the issue of confidentiality. Despite some authors describing favourable patient and user acceptance of Google Glass in their respective clinical experiences, the majority of the included articles referenced concerns over the ability of existing wearable devices to sufficiently manage and protect private information. For example, clinical users of Google Glass must delete any stored information that is sensitive in nature before connecting to WiFi, as the device automatically uploads stored files to Google servers on establishing an internet connection.⁵ This issue may

be partially addressed through the development of medicine-specific software applications that conform to regulations surrounding patient data ownership.^{1 5 23} Transparent organisational policies regarding the use of intraoperative information collected using wearable devices will also be critical from the user's point of view to ensure that recorded data are used constructively rather than punitively.^{12 20 33}

The lack of methodological homogeneity across the articles included in this study impeded the synthesis of robust conclusions regarding the impact of intraoperative applications of wearable technology, and this is indeed one of the limitations of this review. The inclusion of commentary and editorial articles may have contributed to this issue, but it was our view that these article types provided informative accounts of initial experiences with wearable technology in the operating room in the absence of clinical trials. Their inclusion also allowed us to acquire a broad understanding of the quality of the available literature, which further highlighted the need for more formal primary research.

In conclusion, wearable devices hold promise for a number of intraoperative specialties with applications in the broad categories of education, safety and efficiency, communication and information management. Moving forward, it will be essential to address the technological limitations of existing wearable technology, develop healthcare-specific applications, and integrate privacy-protecting safeguards before it may be feasible for wearable devices to seamlessly integrate into the operative environment. The subsequent execution of robust clinical trials will then be needed to elucidate the holistic clinical impact of wearable devices on intraoperative users, processes and outcomes.

Correction notice This article has been corrected since it was published Online First. The following sentence in the abstract: 'To provide an objective overview of the available literature' has been amended to read: 'The objective of this article is to provide an objective overview of the available literature...'

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