On the suitability of current Augmented Reality head-mounted devices

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Abstract

Simulation is a recognized and much-appreciated tool in healthcare and education. Advances in simulation have led to the burgeoning of various technologies. In recent years, one such technological advancement has been Augmented Reality (AR). Augmented Reality simulations have been implemented in healthcare on various fronts with the help of a plethora of devices including cellphones, tablets, and wearable AR headsets. AR headsets offer the most immersive experience of the AR simulation as they are head-mounted and offer a stereoscopic view of the superimposed 3D models through the attached goggles overlaid on real-world surfaces. To this effect, it is important to understand the performance capabilities of the AR headsets based on workload. In this paper, our objective is to compare the performances of two prominent AR headsets of today, the Microsoft Hololens and the Magic Leap One. We use surgical AR software that allows the surgeons to show internal structures, such as the rib cage, to assist in the surgery as a reference application to obtain performance numbers for those AR devices. Based on our research, there are no performance measurements and recommendations available for these types of devices in general yet.

Introduction

In an attempt to measure the feasibility and effectiveness of using AR in surgery and nursing education, we developed an application titled ARiSE (Augmented Reality in Surgery and Education) [39]. We incorporated two facets of this application, one to be used during surgery in the Operating Room (OR), and another to assist in the education of nursing students. Surgeons would use this application in the OR during rib-plating surgery and be able to visualize an accurate model of the patient's rib cage derived from computerized tomography (CT) scans outside their body. The nursing education application would be used by nursing students during the training of fundamental cardiopulmonary physical assessment skills. The students will be able to visualize stock models of various human organs overlaid on manikins along with visual guides to correct auscultation assessment.

The aforementioned applications were developed and deployed into the first generation Microsoft Hololens and Magic Leap One AR headsets for practical use. While the application was deployed successfully and demonstrated accurate usability in both devices, our objective in this paper was to measure and compare the performances between the two AR headsets to derive recommendations for when to use which of these devices.

The contributions of this paper are as follows:

1. Direct comparison of head-mounted augmented reality devices from the major brands, namely Microsoft and Magic Leap.
2. Expert evaluation based on real-world application tested with the help of domain specialists.
3. Recommendations for head-mounted Augmented Reality devices.

Related Work

In this section, we discuss some of the other works that relate to our project and use augmented reality techniques and devices. The related work is split into separated subsections with AR being the common theme applied to different medical areas.

Augmented Reality in Mobile Devices for Medical Learning

Required clinical content cannot always be imparted in live settings due to various restrictions. Educators have instead started using simulation to enhance clinical education. AR simulations have been used to assist the teaching of emergency situations, procedural training, and anatomy [35]. One such AR simulation is described by Von Jan et al. [1] in their paper. The researchers present an application that may be implemented on cellphones and tablet devices that present life-like scenarios which are overlaid on real-world objects. The trainee would visualize these scenarios through their mobile or tablet devices. This application is called mARble, and the researchers report their findings that indicate that AR enhances learning in medical education settings, specifically for subjects that are visually oriented.

Augmented Reality Used in Education

In their paper, Steve Chi-Yin Yuen et al. [13] have implemented AR in education and training and evaluated its efficiency. The researchers discuss the applications of AR in various fields including architecture, advertising, entertainment, medicine, gaming, books, travel, and the military. With respect to medical education, their results show AR enhancing surgical procedures and aiding clinical procedures by enhancing efficiency, reducing cost, and improving safety. The researchers also state that AR ahs the potential to invent new clinical and surgical procedures. AR has been integrated with existing medical equipment by Fischer et al. in their research [17]. There has also been research that claims AR to have the potential to make surgery minimally invasive [13] and also to enhance the learning experience in educational settings [29]. Chien et al. have used AR to assist in teaching students the anatomy of a 3D skull [16]. Researchers have also demonstrated that AR may enhance the teaching of human anatomy [19].

AR in Nursing Education

Wuller et. al. have reviewed existing AR research to assist nursing education [30]. Foronda et. al. have described 3 types of AR applications used to supplement nursing education

[6]. Researchers use the Microsoft Hololens to overlay muscles and bones of the human anatomy on manikins. Rahn et. al., overlay 3D models of human organs in real-time on students using iPads[31]. AR was also used with the help of iPads by Abersold et. al. in their study to assist in the training of the placement of the nasogastric tube(NGT) [32]. Ferguson et. al. have claimed game-based AR applications as having the potential to enhance nursing education [33]. This is also supported by Garrett et. al. who demonstrate improved nursing and clinical skills acquisition in students who participated in AR training scenarios [34].

Simulating Surgeries

Scott Delp et al. have reviewed the shortcomings of educating medical personnel in providing appropriate emergency care [2]. In their research Samset et al. [14] developed AR tools for minimal invasive therapies (MIT). Scenarios presented by them include liver surgery, liver tumors, and cardiac surgery. With the help of AR the researchers superimpose real-world objects with 3D models obtained from CT scans. Results demonstrated improved surgical procedures and hence the potential of AR to improve healthcare in terms of utility, quality, and cost-effectiveness. Other research has also been conducted with regards to using AR during surgery. Kawamata et al. describe an AR application in their research that assists in the surgery of pituitary tumors [18]. Their results demonstrated this type of AR navigation allowing surgeons to perform accurate and safe endoscopic operations on these tumors.

Memory Retention While Using AR

Using Steady State Topography (SST) brain imaging to examine the brain activity of people who participated in AR and non-AR tasks, Heather Andrew et. al. [12] found that the visual attention is almost double when performing AR tasks when compared to non-AR tasks. The author also found that what is stored in memory is 70% higher for AR experiences [12]. Other studies show that the long-term memory of the learner can be enhanced by using multiple media interactions in the learning process [11]. Adedukon-Shittu et. al. have also demonstrated the effectiveness of AR technology with regards to enhancing memory retention and performance [23]. Other studies have also demonstrated the enhanced knowledge acquisition and retention of adequate memory when using AR as a supplemental tool in the education process [24].

Feasibility of Using AR to Train Resuscitation

Steve Balian et al. [8] introduced a method of testing the feasibility of using augmented reality to educate healthcare providers about administration of Cardio Pulmonary Resuscitation (CPR). Using the Microsoft Hololens to provide users with audio and visual feedback, the blood flow in the human body was superimposed in real time onto a manikin. The study deployed 51 volunteers for this study. The volunteering health care providers were asked to perform CPR using only the Hololens for two minutes. The chest compression parameters were then recorded for this test. The participants generally responded positively to the system. The approach was perceived to be realistic and the AR was considered a helpful tool for training in medical education. Among the volunteers, 94% stated that they would be willing to use this application for CPR training in the future. The further support the notion of AR's usefulness in education, Balien et al. successfully demonstrated another augmented reality tool that proved to be valuable for existing education approaches in medical training[16]. Menon et al. [37] developed an augmented reality application to improve the training of nursing students that showed a measurable improvement in student outcomes. Time and again augmented reality has proven to be advantageous when integrated into education in terms of novelty, memory retention, and knowledge gained [14] [12] [23] [24] .

AR Triage Training for Multi-Casualty Scenarios

The order in which patients are treated can have a detrimental effect on the survival rate of a group of patients. Hence, triage, i.e. selecting the most critical patients based on their chance of survival is crucial. John Hendricks et al. [4] devised a virtual reality simulation that assists medical personnel in their training and military field medics in making appropriate decisions in triage training environments. Their model deploys a scene in which users encounter a virtual patient with multiple injury scenarios. The virtual patients can vary with respect to their injuries as well physiological conditions and these conditions can evolve with time-based on their injuries. The injuries are visually supported by animations, such as bleeding and seizures. Augmented reality headsets were used for the user to observe the scenarios and make appropriate decisions using command options on their headsets to successfully prevent the virtual patient's condition from worsening. A supervisor provided additional support and the supervisor would monitor the decisions the user made through a mobile device, such as a tablet or a mobile phone, wirelessly connected to the AR headset. The supervisor would then evaluate the user's decisions after the simulation finished. The user can then also utilize virtual medical devices in this simulation to apply medications as needed. Various types of injuries can be presented in these scenarios, such as gunshot wounds and injuries resulting from the blasts requiring amputations or treating burns, blunt trauma, and chest injuries. Additionally, virtual patients could also be superimposed onto a manikin to allow the user to perform the necessary actions on the manikin. Based on the simulation experience, users then assign triage priorities to the virtual patients and dispense immediate care as needed [4]. Other studies for using enhancing triage systems for emergency medical services using augmented reality can also be found in the literature [26].

Another study has been introduced by Andrei Sherstyuk et al. [5]. In this paper, the authors have proposed a system using a head-mounted display that is supported by external sensors connected to gloves in order to train medical personnel in a triage situation using body poses and hand gestures as user input in a virtual environment. This study found the use of this form of input is beneficial for alleviating the inherent shortcomings of virtual reality headsets, such as claustrophobia, and tunnel vision. The participants in this study were able to travel to multiple virtual casualties/patients using body poses and select tools using gestures in order to perform the required medical operations on the virtual patient. The primary focus of this study was the efficacy of navigation and travel to a virtual patient using body pose commands as input and also object manipulation using gestures. Stuart et. al. presented an AR application that enabled the user's development of proper skills for correct stress management by using virtual patients that appear overlaid on real-world environments [27]. The use of augmented reality headsets typically significantly diminishes some of the aforementioned shortcomings of virtual reality headsets as one is not completely detached from the real world. In addition, hand gestures can be used to navigate the application when using the Hololens, and use the handheld controller while using the Magic Leap One device [37]. Munzer et. al. review demonstrated that AR's feasibility and utility not only in patient-care and operating room settings, but also in training and educating emergency response personnel [25].

System Design

We used Unity 2019 to develop our application with the help of the C# programming language for scripting our implementation. 3D models were created and manipulated in Blender and exported in .obj, .fbx, and .stl formats. We chose to implement our application on the AR headsets Microsoft Hololens and the Magic Leap One devices because they provide larger computational capabilities and fields of view when compared to other AR headsets, such as the Epson Moverio BT-35E. Magic Leap One devices constitute three hardware parts, including the lightwear (wearable headset), the lightpack (processing unit connected to the headset), and the control (wireless controller). The lightpack is designed to easily fit in one's pocket, or be clipped onto one's garments. The Hololens is a one-unit device, which is a wearable headset that uses hand gestures and voice commands for interactive operation.

We used Magic Leap's MLSDK, version v0.23.0 in order to develop our application in Unity 2019. Magic Leap One devices have the following specifications: The CPU is an NVIDIA® Parker SOC with 2 Denver 2.0 64-bit cores + 4 ARM Cortex A57 64-bit cores (2 A57's and 1 Denver accessible to applications). Its GPU uses an NVIDIA Pascal™, 256 CUDA cores chip along with the following Graphic APIs: OpenGL 4.5, Vulkan and OpenGL ES 3.1+AEP. It has an 8 GB RAM, and 128 GB storage capacity. Audio inputs include voice (speech to text) + real world audio (ambient), and audio outputs include onboard speakers and 3.5mm jack with audio spatialization processing. The device also comes with Bluetooth 4.2, WiFi 802.11ac/b/g/n, and USB-C connectivities. The lightpack compute unit has a built-in rechargeable lithium-ion battery that could last up to 3 hours with continuous use and could be charged using a 45-watt USB-C fast charger. In contrast, Microsoft's Hololens has 2 GBs of RAM, a 64 GB flash memory for storage, and an Intel 32-bit (1GHz) processor with TPM 2.0 support with a custom-built Microsoft Holographic Processing Unit (HPU 1.0).

Our application was designed and developed using Unity 2019 and C# scripting. We added our 3D models and our functionality managers as game objects in the Unity hierarchy. Prefabs like input managers and spatial mapping were added to adapt our requirements, whereas the 3D models were dynamically added to the hierarchy as prefabs using our C# code. The model prefabs were designed to be turned active or inactive using UI buttons and voice commands that were made available to the user. We also added prefabs to handle dependencies and the proper functionality of the application. We used raycasting in our application to shoot a straight invisible "ray" out in the forward direction from our controller for selection purposes. This ray is made visible to the user upon collider detection as a blue line that extends from the controller to the collider object. Colliders had been added to 3D models and buttons for selection purposes using raycasting. Supplementary software development kits (SDKs) were also used for the development of these applications, namely the Magic leap SDK (MLSDK-version v0.23.0), Windows Mixed Reality Toolkit (MRTK) and Vuforia. Blender was used to develop the 3D models which were then added as prefabs to Unity. For the Hololens, we had to rely on gesture input only as it does not come with a separate controller.

The surgery application consisted of the 3D model of the patient's rib cage. The nursing education application consisted of the following 3D models - lungs, heart, rib cage, chest, auscultation guide, and defective lungs. For the surgery application, we received CT scans from our collaborators at Premier Health Miami Valley Hospital in Dayton, Ohio. These CT images were in the DICOM format. We then imported these CT scan images to ParaView, where we processed the CT image to eliminate unwanted structures and retrieve the desired rib cage 3D model in the .stl format. The processing was performed with the help of the following filters- contour, decimate, connectivity, and threshold. The contour filter is used to create the isosurfaces and isolines for the 3D model. The decimate filter is used to simplify the polygonal model and reduce its geometric complexity. The connectivity filter identifies the connected structures. The threshold filter allows us to extract parts of the polygonal dataset whose scalars lie in a specified range. The connectivity and threshold filters were used to remove any unwanted noise present in the 3D structure, such as noises that may be present in the intercostal spaces of the ribcage.

The heart and lung models in the nursing education application also contain anatomically accurate animations attached. The defective lung model contains animations that simulate a collapsed lung in which only one side of the lungs is moving. We also added sounds to our heart and lung models. Heart sounds included were the regular S1 and S2 sounds, which are caused due to the closing of valves [28]. Our application consisted of five variations of lung sounds including bronchial, bronchovesicular, vesicular, tracheal, and wheezing sounds. Our objective was to allow the user to observe normal and abnormal activities of the heart and lungs both visually and through audio depending on the training scenarios.

Somosky et al. have demonstrated the advantages of using AR to provide students an internal view of the anatomy of a chest cavity [15]. AR offers enhanced learning capabilities for nursing students with its use of visual imagery as an added benefit to standard teaching methods [6]. Our application allows students to visualize the functioning of human hearts and lungs animated in an anatomically accurate fashion. The placement of the 3D models can be achieved manually by adjusting the placement or by using a Quick Response (QR) marker that we custom developed for this application, having dimensions 1cm X 1cm. This QR marker may be removed once the placement of the 3D models has been achieved. For accurate placement, we place the QR code on the sternum, right below the jugular notch, on the manikin or the volunteer. This QR code is not mandatory as 3D models can be placed anywhere manually using the spatial mapping mechanisms present in both AR headsets. However, it is being implemented here for accuracy and ease of use. We use the Vuforia SDK's image target detection to locate the QR marker for accurate model placement [7]. The QR marker is added as an image target prefab to Unity's hierarchy. A device-based demerit that applies to both the Magic Leap and Hololens devices is that they tend to displace the 3D models by a small measure in the screenshots and video-captures taken during operation.

The software was used for multiple surgeries so far and over thirty students for training purposes. We collected feedback from the surgeons and the students both in the form of testimonials and a feedback form. Figures 1 and 2 show the screenshots of ARiSE being used in the surgical and nursing education settings respectively [39].

Figure 1. *Hololens Screenshot of Surgeons Using ARiSE on a Cadaver*

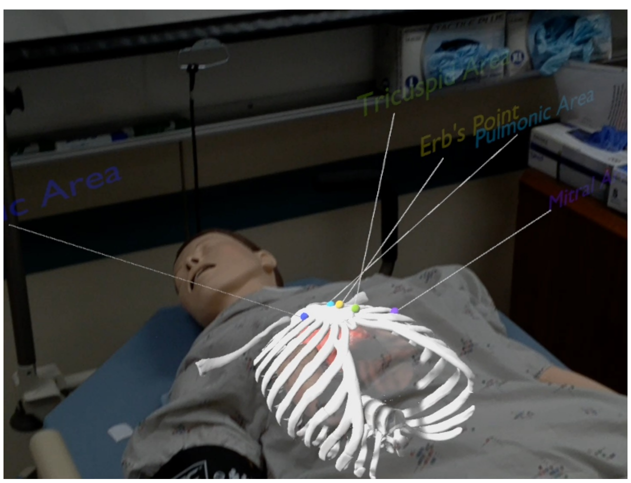

Figure 2. *Magic Leap One Screenshot of Nursing Students Using ARiSE on a Manikin for Training*

Results

We compared the two devices based on different criteria, including performance, usability, ease of use, and comfort guided by the two applications described earlier. We solicited feedback from two surgeons and over 50 nurses and nursing students to gauge the experience with these devices with respect to these criteria.

To compare the rendering performances between the two devices we performed a frame rate test while rendering the same rib cage model on both devices for a duration of 60 seconds. The rib cage model used for our frame rate test is shown in Figure 1. The rib cage model was visualized on both devices separately

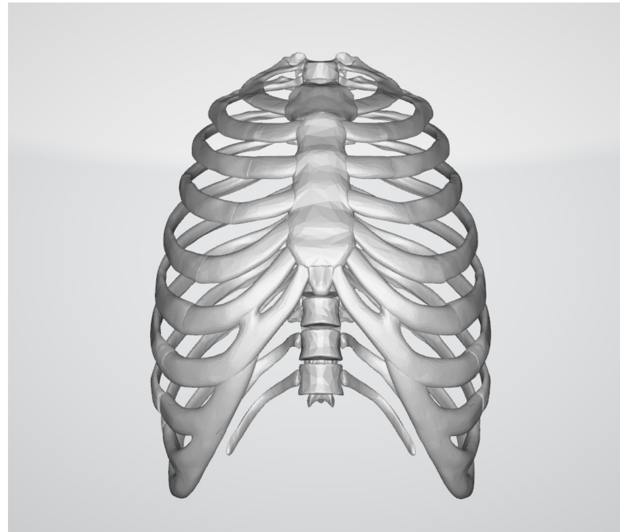

Figure 3. *Rib Cage Model Used For Comparison*

over a period of 60 seconds while running an FPS counter. The rib cage model was 6.46 MB in size and had 232625 triangles and 697875 vertices. Boghosian et al. state in their study that the recommended number of triangles to alleviate jitter in the Hololens is 200,000 and to allow for usability is 250,000 [36]. The Magic Leap One has a higher threshold for constraints on performance. After analyzing our test results, the Magic Leap One demonstrated an average frame rate of 59.46 frames per second (fps) while having the rib cage model in the camera's field of view. For the same test, the Hololens only demonstrates an average frame rate of 8.9 fps. These results are visualized in the chart present in Figure 2.

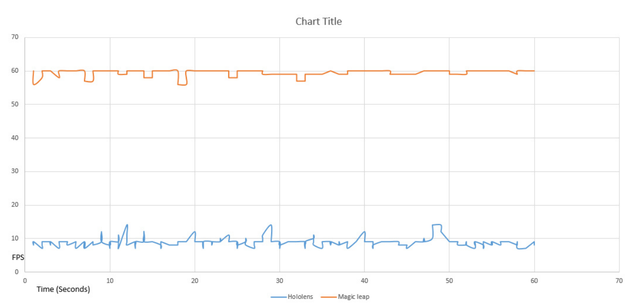

Figure 4. *FPS Comparison Between Microsoft Hololens and Magic Leap One*

Table 5 shows most of the main characteristics for a direct comparison of various metrics. The Magic Leap One has slightly higher vertical display resolution and an overall higher field of view resulting in a larger overlay on top of the real world that the augmented reality application can take advantage of. The Hololens is heavier due to the fact that it contains all computing equipment in the head-mounted device. It therefore also puts 33% more weight on the user's nose making the Magic Leap a little more comfortable to wear. The Magic Leap One has twice the storage capacity and four times the memory. Combined with the better GPU processing capabilities, this allows the Magic Leap to handle larger 3D models which in our application enables us

	Microsoft Hololens 1	**Magic Leap One**
Resolution (per eye)	1280×720	1280 x 960
Field of View	34 degrees	50 degrees
Weight: Nose pad Back Overall	 366 g 274 g 579 g	 238 g 80 g 316 g
Storage	64 GB	128 GB
Memory	2 GB	8 GB
Input modalities	Gesture, Voice	Gesture, Voice, Controller
Price	\$3000-\$5000	\$2300
Recognized hand gestures	2 gestures	9 gestures

Figure 5. *Table showing specifications for head-mounted display systems.*

to use a higher fidelity for the augmented rib representation and internal organs.

The programming modalities distinguish the two devices as well. The Magic Leap One can be viewed as a stand-alone computing unit where one can access files in the conventional fashion whereas the Hololens requires one to use a Microsoft account to upload to and access files from.

The students and surgeons generally provided very positive feedback both in the form of testimonials as well as through a feedback form the students filled out after their AR training sessions. The surgeons testified that ARiSE made the location of fractures in the rib cage easier and hence helped to reduce the size of the required surgical incisions. The surgeons also stated that they preferred using the application on the Magic Leap One device the Hololens. The benefits of the Magic Leap from the surgeons' perspective was the smaller footprint of the Magic Leap One and the fact that it allowed us to render higher-resolution models due to the increased rendering performance.

Students who used our software with the Magic Leap One responded with very positive comments, such as *"This is so cool!"* and *"That's crazy. I want to touch it! This just really gives you perspective, you know."* One student pointed out that using the AR is significantly more helpful than using cadavers for studying as it presents the internal organs in an intact and undisturbed manor and also allows for animations of the lungs and heart. Overall, we received consistently positive testimonies from students stating that ARiSE helped enhance the training experiences. A total of 55 students participated in our study. Students were also asked to complete a feedback form that was used to analyze student self-confidence and satisfaction with respect to using ARiSE in a simulation setting. The feedback form consisted of 13 items, 5 questions related to self-satisfaction and 8 related to self-confidence. Students were asked to answer each question based on a 5-point Likert scale ranging from "Strongly Disagree" (1) to "Strongly Agree" (5). Analysis of this data demonstrated high confidence and satisfaction rates in Students. The lowest average mean for any question was 4.5 out of 5, with a standard deviation value of 0.52 [39]. Similar to the feedback from the surgeons, the nurses and nursing students liked the Magic Leap One better. The increased rendering performance allowed us to include additional organs at higher fidelity. The small footprint of the device made the device non-intrusive allowing them to follow their usual training protocol with a physical manikin, stethoscope, and left their hands available to feel for pulse etc. while the AR provided additional information and insights that would not otherwise be available.

Discussion

Our results demonstrate the Magic Leap One devices having a higher threshold for performance constraints when compared to the Microsoft Hololens. We experienced jitter and dropped frames on the Hololens when using the same application. The Magic Leap One devices are capable of handling larger file sizes with more complex polygons. A more seamless user experience was observed while using the Magic Leap One during the implementation of our surgery and nursing education applications. For optimal visual fidelity without adversely affecting performance on low fidelity scenes that only have 1-3 objects per scene, Microsoft recommends a total triangle count of fewer than 100,000 triangles [38]. Based on this, as well as the results of our FPS test, the Hololens would be an ideal candidate for low-fidelity scenes (1-3 models per scene) having less than 100,000 triangles, medium fidelity scenes (4-10 objects per scene) having less than 30,000 triangles, and high fidelity scenes (Over 10 objects per scene) having less than 10,000 triangles. For scenes that have objects with a more complex triangle count (Over 100,000 triangles), the Magic Leap One would be more ideal.

Direct hands-free input, such as voice commands and hand gestures can be very useful with these types of devices. This allows the user to still handle real-world objects at the same time while using these devices. However, this type of input can lack precision at times. Hand gestures may not be recognized as reliably resulting in the need for repeating input commands. Voice commands sometimes are not understood properly and have to be repeated. The Magic Leap One comes with an input controller in addition to accepting gesture and voice input. This controller is fully tracked and provides very accurate input capabilities. Typically, the input controller is used with a ray casting metaphor in which a line emanating from the controller is projected onto an object that can be selected with a button press. The 3D tracking of the controller is very accurate with no perceivable jitters or deviation which would be significantly amplified with the ray casting. We received testimonies from surgeons who used our applications on live patients in the operating room stating that they preferred using ARiSE on the Magic Leap One over the Hololens for its enhanced user experience. The surgeons stated that they experienced some jitter with the 3D model in the Hololens, which they did not experience in the Magic Leap One.

Generally, the Magic Leap One outperformed the Hololens both in terms of rendering performance and level of comfort due to the lower weight. It was very well received by the participants in our studies as well. The main differentiator between the two devices is the external compute device (lightpack) versus everything being integrated into a single device and the fact that the Hololens can be used with prescription glasses whereas the Magic Leap One cannot. Instead, special inserts with prescription lenses have to be used. Unless one of those criteria poses an issue for the envisioned application, the Magic Leap One appears to be the better device for many augmented reality applications both in terms of compute capabilities and comfort. The dedicated controller can make user input more precise thereby improving the ease-of-use for the Magic Leap One compared to the Hololens.

Conclusion and Future Work

Our results demonstrated the Magic Leap One device performing better than the Microsoft Hololens in terms of frame rate and less jitter when running our application on both devices. Albeit, the Magic Leap One devices have more components attached to the device when compared to the Hololens, namely the lightpack, the lightwear, and the handheld control, whereas the Hololens only consists of the wearable headset which handles the processing as well as the display. As a result, the wearable Hololens headset is heavier than the headset unit of the Magic leap One, weighing in at 579 g (1.28 lbs). The Magic Leap One's lightwear only weights 316 g (0.69 lbs). Magic Leap offers prescription lens inserts that may replace the existing default glasses. Microsoft Hololens does not offer this feature, however, the headset can go over the user's glasses, but may cause some discomfort depending on the glasses.

There are comfort factors to be considered in both devices. The Magic Leap One consists of three separate components, including a handheld control, thus having more parts around one's person of which to keep track. The Hololens is a slightly heavier device, but is less intrusive when compared to the Magic Leap One as user interaction is achieved primarily through hand gestures and voice commands. However, the Hololens may cause small amounts of discomfort to users who wear glasses. Based on the design of the two devices, the Magic Leap One and the Hololens headsets distribute their weights differently. The Magic Leap One weighs 238 g (0.52 lbs) at the nose pad present at the front of the device, and 80 g (0.17 lbs) at the back of the wearable headset. Meanwhile, the Hololens weighs 366 g (0.80 lbs) on the nose pad, and 274 g (0.60 lbs) at the back of the wearable headset. The significantly lower weight on the nose makes the Magic Leap One more comfortable to wear for the user as a result.

Based on performance capabilities alone, our results and feedback we received demonstrate the Magic Leap One devices performing better than the Hololens for the purposes of surgery and nursing education simulations.

The researchers intend to further compare the different existing AR devices in a wider variety of applications, as well as any that may be released to the public in the future. We believe that an in-depth performance review is imperative to identify the best device based on application needs.

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