Autonomous Robotics and AI in Trauma and Emergency Care for Space Medicine

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12.1 Trauma and Emergency Care in Space Medicine

The National Aeronautics and Space Administration (NASA) has long envisioned the expansion of human space travel beyond Low Earth Orbit (LEO). With the Artemis missions under active development, NASA is planning to establish a sustainable human presence on the Moon, which will usher in the discovery of new scientific knowledge, open possible commercial activity, and help prepare for exploration missions to Mars [1]. Private aerospace companies are also on the rise, with six major companies emerging just in the US since 2000 [2]. SpaceX, for

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example, is currently partnering with NASA on some of the Artemis missions [3], while also leading efforts on deep space travel for future Mars colonization missions [4].

With deep space human exploration becoming a reality, preparing to manage health emergencies aboard a spacecraft is paramount. In fact, Schneider et al. published a summary of the "Spaceflight for Everybody" symposium focusing on identifying health risks and corresponding countermeasures for long-duration space travel [5]. A "traffic light" rating scale was proposed to classify the severity of adverse event risks based on mission length, distance from Earth, and space radiation exposure. While missions in LEO typically see risks classified as green or yellow, with only about 15% categorized as red, Mars missions—whether in orbit or on the surface—see nearly half of the risks fall into the yellow or red categories, foreboding more severe consequences [6]. This approach to risk assessment in space missions mirrors the challenges in similarly isolated environments, like on US submarines, where crew injuries were found to be the primary cause of morbidity and downtime [7]. Similarly, in remote areas like Antarctica, comprehensive mass casualty incident response and aeromedical evacuation plans are in place due to the region's extreme remoteness and heightened risk [8].

Medical interventions are deemed necessary within space programs to address emergency conditions [9]. Although numerous studies have indicated that illnesses and injuries requiring major surgery during spaceflight are expected to be rare [10], the occurrence of such events can have a detrimental impact on the mission, resulting in compromised returns to Earth and mission aborts. As we venture further into space and for longer periods of time, understanding what injuries and illnesses astronauts might sustain becomes crucial for effective preparation and response.

12.1.1 Injury and Emergency Profiles in Prolonged Space Exploration

Astronauts undergo extensive screening for chronic and heritable diseases. Traumatic injuries, however, can be sustained unexpectedly even by the healthiest individuals. The primary concern with injuries in microgravity is hemorrhage, which becomes life-threatening if it progresses to major traumatic hemorrhage. Hemorrhages are classified as compressible or non-compressible based on their location and responsiveness to simple compression methods [11, 12]. Non-compressible torso hemorrhages, which may arise from major vascular trauma, pulmonary parenchyma, solid abdominal organs, or pelvic disruptions, are particularly perilous as they are often occult [12]. Managing such injuries presents profound challenges despite diagnostic advancements using ultrasound (US), and immediate surgical intervention is frequently necessary before precise localization of the bleeding source is even possible [9]. During the construction phase of the International Space Station (ISS), there was a heightened risk of trauma, including crush injuries, lacerations, and thermal and electrical burns [13, 14]. Through careful planning of crew safety, astronauts have only experienced minor injuries, such as lacerations and finger pinching [14]. While there have been several catastrophic fatalities, to date, no evacuations due to serious trauma have been required in space [9]. The most common medical incidents reported in the Shuttle-*Mir* orbital program involved only minor traumatic injuries to the skin and mucous membranes [15].

Deep space exploration, however, exacerbates existing conditions. Research has shown that the medical event rate is directly proportional to the mission duration [16]. A correlation was also identified between extravehicular activity (EVA) and the onset of illnesses and injuries, particularly relating to fractures, trauma, and radiation exposure from solar particle events [17]. Future long-duration missions to the Moon or Mars will require up to 24 h of EVA per week, compared to the typical 3–4 h during a 6-month stay on the ISS [18]. Additionally, in environments with reduced gravity—such as those with a third or sixth of Earth's gravity—objects may seem deceptively light due to weightlessness. Yet, they still retain their mass, potentially enabling serious crush injuries. Hardened protective gear can help shield astronauts from serious thoracoabdominal injuries [11], but their use may impose excessive musculoskeletal strain, thereby elevating the risk of emergency skeletal injuries [9]. Renal stone formation among astronauts is another well-documented condition, with evidence pointing to a higher risk during longer missions [19]. Lastly, emergency medical conditions such as appendicitis and cholecystitis remain concerns in space, as highlighted by reports of sudden abdominal pain among astronauts [9]. The risks and benefits of prophylactic procedures are a topic of debate, meaning that these conditions must still be carefully considered in planning for long-duration space travel.

12.1.2 Challenges of Trauma and Emergency Care in Space

Although astronauts may experience injuries and illnesses during space missions that are similar to those on Earth, the complexity of patient care in long-duration space missions is compounded by multiple factors. We categorize these factors into three distinct areas, namely environmental conditions, human factors, and technological limitations.

12.1.2.1 Environmental Conditions

Physiological Changes Space travel has profound physiological effects on astronauts, which can complicate any injury or surgical scenario. Certain physiological changes, particularly those affecting the body's ability to withstand and recover from major systemic trauma, are especially critical in emergency medical care. One significant concern is the loss of bone mineral density (BMD) during periods of weightlessness due to reduced loading stimuli. BMD in astronauts decreases at an average rate of 1–1.5% per month, which is ten times the rate observed in osteoporosis [20]. Furthermore, bone resorption and possible decrease in bone formation are only partially responsive to non-pharmacological countermeasures such as exercise and adjusted diet [20]. With bone weakening, the risk of fractures is heightened. The thoracic cage, for instance, protects vital thoracic and abdominal organs like the heart, liver, and spleen. Its weakening means even minor blunt trauma can lead to organ injury and uncontrolled internal hemorrhage, requiring immediate surgical intervention. Moreover, the calcium released from bone resorption is excreted in the urine, which can lead to the formation of renal stones [21].

Cardiovascular changes have also been observed in microgravity. In a recent publication, Gallo et al. developed and validated a 1D-0D multiscale model to study the cardiovascular response to long-term zero gravity (0G) spaceflight in comparison to the 1G supine reference condition [22]. The authors found that the cardiac work, oxygen consumption, contractility indexes, and central mean and pulse pressures were reduced in microgravity. Additionally, the exercise tolerance of a spaceflight traveler was shown to be comparable to that of an untrained person with a sedentary lifestyle [22]. Other studies have also reported evidence of cardiac remodeling due to conditions of weightlessness [23]. In particular, cardiac atrophy was linked to reductions in metabolic demand and oxygen uptake [24]. Another study documented a 9.1% decrease in left ventricular mass among astronauts [25]. Hemostasis is also adversely affected by gravity reduction, making bleeding a general concern and potentially necessitating novel approaches for effective blood loss control. Fluid redistribution and diuresis in space result in a 10–23% blood volume reduction before any injury even occurs, which is equivalent to a Class I Advanced Trauma Life Support (ATLS) hemorrhage on Earth [26]. Such a reduction decreases cardiac reserve, and the autonomic nervous system's reset increases beta receptor sensitivity, potentially inhibiting effective vasoconstriction [13]. Additionally, the combined effects of microgravity and radiation on human cardiovascular functions are not yet well understood.

Microgravity also dysregulates the human immune system. The number and function of white blood cells are altered, with studies showing a redistribution of peripheral leukocytes, diminished function of specific leukocyte subpopulations, and skewed cytokine profiles in many astronauts [27]. While the adaptive immunity is dysregulated during space flight, some aspects of the general immunity are heightened, with an altered interaction observed between the two [27]. Wound healing was shown to be impaired in space as well, with studies on rat abdominal incisions demonstrating greater inflammatory responses [28]. With a potentially weakened immune system, the greater bacterial growth observed in weightless environments becomes a further complication [29]. Bacteria were shown to develop thicker cell walls and increased resistance to antibiotics, as evidenced by post-flight samples collected from the crew of the Apollo-Soyuz Project [30]. The effect of increased radiation exposure, which also affects the astronaut's immunity and proliferation of rapidly dividing cells, has not been adequately studied either.

Procedural Changes Microgravity complicates surgical interventions from a procedural standpoint, too, affecting both the human body's physical response to the surgery and the execution of the surgery itself. For instance, arterial bleeding can form droplet streams, and venous bleeding can form domes, which swell like balloons before leaving the vessel [26]. Blood drops can also adhere to surgical instruments and wound areas due to surface tension. Precise surgical maneuvers are more difficult to execute, as organs that normally rest in place now float in space. Laparotomy, which entails creating a wide incision in the abdomen to access the peritoneal cavity, is often performed on emergency trauma patients but may not be practical in 0G conditions. Similar challenges are observed in laparoscopy. A laparoscopic porcine study showed that in weightlessness, the bowel in the supine position does not remain posteriorly retracted and exerts pressure on the anterior abdominal wall [31]. The anterior bowel flotation, compounded by floating blood, bodily fluids, and debris, can obscure the surgical field and increase the risk of contamination. Maintaining sterility in the surgical workspace is another concern. The spacecraft environment increases the risk of infection due to the possible presence of floating bodily fluids and surgical debris. The limited space onboard means that the surgical area might be uncomfortably close to the non-sterile galley or exercise facilities [32]. Furthermore, patients, surgical personnel, and hardware must all be securely restrained to prevent unintended movement, introducing additional discomfort and risks.

12.1.2.2 Human Factors

Personnel Availability Presently on the ISS, a Crew Medical Officer (CMO) is responsible for the healthcare of astronauts. A CMO is not necessarily a physician but is an astronaut who has received 40–60 h of medical training [33]. CMOs must be proficient in key medical procedures, such as those outlined by the ATLS protocols [34], including intravenous insertions for infusions, endotracheal intubation, and chest tube placement [8]. While trained in a wide range of medical and non-medical subjects, CMOs lack the specialized surgical skills that would be needed, particularly for more complex clinical cases. The general consensus is that surgical trauma procedures in space would be best handled by two surgeons [35]. However, the presence of even one space surgeon in future long-duration missions may not be guaranteed [35]. Non-physician CMOs are currently favored over surgeons because they can undertake a variety of activities other than medical treatment, making their versatility a key asset in the constrained and resource-limited environment of a spacecraft. At the same time, this compromises the CMO's capacity to devote time and attention to medical emergencies. Additionally, trauma and emergency surgery on Earth require the support of an entire medical team. Space missions do not have the luxury of nurses, anesthetists, and other support personnel who play critical roles in providing medical care on Earth.

Personnel Training To better prepare astronauts, space missions are emulated on Earth through various analog environments, simulations, and training programs. Analog missions such as NASA Extreme Environment Missions Operations (NEEMO) underwater off the coast of Florida [36], *Hawaii* Space Exploration Analog and Simulation (HI-SEAS) on the slopes of Mauna Loa in Hawaii [37] and missions on the Concordia Station in Antarctica [38] provide valuable opportunities for astronauts to experience the isolation, confinement, and operational challenges of long-duration space travel. However, training for surgical procedures in microgravity remains particularly challenging. While various setups exist to test equipment for space missions, realistic surgical training in reduced gravity can only be achieved through parabolic testing [39]. Parabolic testing takes place on an aircraft executing a series of parabolic maneuvers, ascending and descending at 45° angles to create 20–30 s of microgravity during each transition, repeated 30–40 times [40]. Multiple studies have demonstrated the feasibility of laparoscopic surgeries on porcine models during these flights [31, 39]. Thoracoscopic surgeries, however, proved to be more difficult and were less successful [39]. Although parabolic flights are useful for simulating microgravity, the duration of weightlessness provided is insufficient to realistically replicate the complexity of performing a full surgical procedure in space. To date, only minor medical procedures, such as treatment of superficial lacerations, have been performed on the ISS. Future trips to the ISS for surgical training are unlikely, as they are prohibitively expensive and time-consuming. Virtual Reality (VR) could augment surgical training capabilities, though the ecological validity of this approach is currently only partially understood. Additionally, the unpredictability of space travel makes comprehensive preparation and training extremely challenging.

12.1.2.3 Technological Limitations

Distance and Communication Space missions to date have primarily taken place on the ISS. On these missions, astronauts are a select group of healthy individuals who attend a weekly private medical teleconference with a flight surgeon on Earth who monitors their health status [35]. The astronauts can also evacuate to a Soyuz capsule from LEO and return to Earth within a few hours if a critical condition arises [35]. However, for future missions involving greater distances, immediate communication and evacuation to Earth will not be feasible. For instance, a return trip from the Moon to Earth can take 6–7 days, while a journey from Mars will last anywhere between 18 and 24 months [35]. Communication between the Earth and Moon, with an average distance between the two of about 384,400 km, experiences a delay of approximately 1.28 s each way [41]. This delay increases dramatically for Mars missions, where the distance to Earth ranges from 54.6 million to 44 million kilometers, resulting in a communication latency of about 6–24 min [35]. The "golden hour" rule, for example, stipulates that critically injured patients must receive definitive care within one hour of sustaining an injury to reduce the risk of death or disability [42]. Communication delays that span tens of minutes can easily surpass this critical timeframe, making timely patient stabilization even more challenging. Furthermore, the limited bandwidth for data transmission restricts the amount and quality of data that can be sent to Earth. Such limitations render Earth-based telemedicine support to astronauts in space impractical in critical situations.

Mass, Volume, and Power In space travel, mass limitations are dictated by the rocket's payload capacity. Every additional kilogram requires more fuel not only to leave LEO but also to enter, maintain orbit around, and leave the surface of the Moon or Mars. Current estimates for NASA's space shuttle launch are US$54,000 per kg. With a payload of 27,500 kg, this amounts to a total of US$1.5 billion per launch [43]. For context, the da Vinci Xi surgical system, including the surgeon console, patient cart, and vision cart, weighs a total of 1344 kg [44], adding approximately US$72.5 million in costs if transported aboard a spacecraft. Although commercial launch systems such as SpaceX's Falcon 9 have reduced launch costs by about four times, the need for specialized equipment increases the costs and reduces the payload capacity [43]. In tandem with mass restrictions, the volume of items to be transported is also limited, given the confined space of the shuttle. Power limitations result from the finite amount of energy available, typically supplied by solar panels and batteries. Efficient energy management is critical to ensure that essential systems, including life support, communication, and scientific instruments, operate continuously. As spacecraft travel farther away from the Sun, they require larger solar panels to capture sufficient energy, which adds weight and further limits the amount of equipment that can be carried on board.

Equipment and Auxiliary Support As a direct outcome of mass, volume, and power limitations, only specific medical equipment and systems can be transported aboard a spacecraft. Devices such as Computed Tomography (CT) scanners are currently excluded from long-duration space missions. Magnetic Resonance Imaging (MRI) scanners present even greater challenges, weighing approximately 11 tons and requiring constant helium cooling of their superconducting magnets. The emitted stray magnetic fields from MRI scanners can also interfere with spacecraft operations [45]. Initiatives have been undertaken to miniaturize robotic systems and streamline their designs to include only essential components [46], but these systems remain in the experimental phase.

The variety and quantity of medical and surgical tools that can be carried are also restricted. Medications, blood, and fluids are limited and subject to expiration. On the ISS, the only available resuscitation fluids are 4 L of normal saline [47]. Methods to generate crystalloids in flight are still under investigation [48]. Blood transfusion, whether for surgical support or standalone treatment, is currently not possible. Only lyophilized blood components, such as plasma, which may be stored for up to a year, are suitable [47]. An alternative involves hemoglobin-based oxygen carriers, which are artificial substitutes for red blood cells that can deliver oxygen and provide volume expansion [47]. These substitutes are convenient as they require minimal preparation, but they have similar mass and volume to packed red cells and will thus consume a lot of space. They also utilize significant refrigeration power and have a short shelf life of 35 days at 1–6 °C [47].

These limitations undermine the synergistic ecosystem of healthcare present in hospitals on Earth. Effective patient care on Earth relies on the seamless coordination of multiple departments, equipped with diverse facilities, tools, and expertise. In space, the absence of readily available auxiliary support, such as on-demand clinical laboratories and pharmacies, may jeopardize clinical decision support and the quality of long-term patient care.

Data and Testing Much of what we know about the specific challenges posed by space exploration is based on research conducted on the ISS. The actual needs and hazards of performing surgical procedures in deep space remain largely speculative and untested. The collection and interpretation of physiological data from astronauts is far from perfect, as monitoring health conditions in space is, at best, limited and often outright impossible. Furthermore, all existing physiological data is obtained from astronauts who had spent no more than 6–7 months in LEO. Few astronauts have remained in microgravity for longer durations, and those who have participated in extended missions have not been studied extensively to assess potential changes or adverse effects on their anatomy and physiology [5]. Long-duration space exploration missions to Mars, for example, can last at least 34 months, which is more than twice the record for the number of consecutive days spent in space by any astronaut [49]. Lastly, developing effective strategies for testing new space technologies on Earth is crucial for verifying their suitability for future missions, especially in terms of their performance in microgravity. The six main experimental systems for ground verification of a microgravity environment are air-bearing, neutral buoyancy, free-fall, parabolic flight, suspension, and hardware-in-the-loop systems [50]. Each of these systems has limitations, and some are not even suitable for medical and surgical applications. For instance, neutral buoyancy requires submerging the system in water, making it impractical for surgical testing or training.

12.1.3 Procedures for Trauma and Emergency Care in Space

Despite studies on the viability of emergency procedures in microgravity [9, 51], the complex pathophysiology of hemorrhagic shock in space remains poorly understood. In the next section, we will examine procedures for patient stabilization, reconstructive surgery, and acute care that hold promise for adaptation from terrestrial to space missions.

12.1.3.1 Patient Stabilization

Damage control resuscitation (DCR) is a strategy for early initiation of blood product transfusions, crystalloid fluid administration, permissive hypotension, and damage control surgery (DCS). It can be delivered to a critically ill patient in any location (emergency department, interventional radiology suite, operating theater, and/or intensive care unit) [52]. The equivalent protocol designed specifically for austere environments is the Remote Damage Control Resuscitation (RDCR) [12, 53]. In this scenario, permissive hypotension is a valuable support, allowing the control of exsanguination by lowering blood pressure while ensuring vital organ perfusion [54]. This approach requires careful monitoring of the patient’s radial pulse and mental status while maintaining a systolic blood pressure (SBP) between 80 and 100 mmHg. Traumatic brain injury needs a higher SBP (>100 mm Hg for ages 50–69 and >110 mm Hg for ages 15–49) to preserve cerebral perfusion and avoid a secondary ischemic injury to the brain [12, 53]. The early use of blood products, fresh warm whole blood, and other blood components [47] also reflects DCR and RDCR practices. For limb and extremity trauma, tourniquets or hemostatic dressings may be adequate to stabilize the patient [55]. Non-compressible torso hemorrhage is better managed using medical devices such as abdominal aortic and junctional tourniquets, injectable hemostatic sponge, resuscitative endovascular balloon occlusion of the aorta (REBOA), intra-abdominal self-expanding foam, and expandable hemostatic sponges [56, 57].

Topical hemostatics can also play a crucial role in managing medical emergencies in space. A systematic review in 2018 identified four primary categories of topical hemostatics: (1) adhesives (liquid fibrin adhesives and fibrin patches), (2) mechanical hemostats, (3) sealants, and (4) hemostatic dressings (mineral and polysaccharides) [58]. The choice of hemostatic agent largely depends on the patient's endogenous coagulation state. For instance, mechanical agents are preferred after surgical hemostasis or packing if coagulation is normal. For ongoing arterial or high-flow bleeding, adhesive agents with a patch are recommended because they can be directly applied at the bleeding site. Sealant agents are particularly useful for controlling bleeding in organs, such as the liver, pancreas, and kidney, or for sealing lung wounds. Hemostatic dressings are indicated for junctional and non-compressible hemorrhages, such as those in the neck, groin, or axilla. Recent advances have also seen the clinical application of novel hemostats, like self-assembling peptide nanofibers and chitosan nanofibers [58–60].

DCS helps manage severe intra-abdominal hemorrhage, organ damage, and other serious injuries that cannot be treated through non-operative means. DCS also aims to minimize the number of surgical interventions while safeguarding a patient's physiological reserves. This approach not only restricts surgical operations to those that are absolutely necessary but also reduces the need for extensive surgical equipment. Once the patient is prepared for surgery, rapid evaluation and control of bleeding sources are paramount. This may involve techniques such as packing, ligation, or resection of damaged tissues. Temporary abdominal closure techniques, such as the use of negative pressure wound therapy or Bogota bags, help prevent abdominal compartment syndrome and facilitate re-exploration. For managing solid organ injuries, techniques such as splenectomy, hepatorrhaphy, and nephrectomy may be necessary. These procedures require precise surgical skills to control bleeding while preserving as much organ function as possible. If the patient is hemodynamically stable, angiography with selective embolization of bleeding vessels might be performed. Advances in minimally invasive techniques, such as laparoscopic surgery, are increasingly being incorporated into trauma care to reduce recovery time and postoperative complications.

12.1.3.2 Postoperative and Definitive Surgical Care

Postoperative complications following DCS are detected through a combination of laboratory tests, clinical assessment, and imaging studies [61–63]. The patient is monitored for signs of instability, such as changes in vital signs, increased abdominal pain, or decreased urine output, indicating issues like bleeding or infection. Laboratory tests, including complete blood count, coagulation profiles, and blood cultures, provide information on the patient's physiological status and help identify infections or ongoing hemorrhage. Imaging studies using US or CT can detect complications like intra-abdominal abscesses or anastomotic leaks [61, 62]. Postoperative bleeding frequently requires surgical re-exploration. Surgeons may perform methods such as repacking of the abdominal cavity, selective vascular ligation, or bleeding site suture. Angioembolization may be used for specific arterial bleeding identified on angiography, especially if re-exploration poses a significant risk [61]. In cases of intra-abdominal sepsis or abscess formation, surgical intervention involves drainage of pus collections, which can be performed percutaneously via imaging or through open surgical drainage. When an anastomotic leak is detected, surgeons may need to resect the leaking section of the bowel and create a new anastomosis. In some cases, especially if the patient is unstable or the tissue is not healthy enough for a new anastomosis, a diverting stoma, such as an ileostomy or colostomy, is created to facilitate fecal diversion and tissue healing [63]. Contaminated wounds may require surgical debridement to remove infected tissue, followed by wound care procedures such as negative pressure wound therapy [64]. Abdominal compartment syndrome is another potential complication. It is characterized by increased intra-abdominal pressure that can impair organ function. Surgical decompression through laparotomy is often necessary to restore blood supply to vital organs and prevent further organ damage [65]. It is not uncommon for patients to require future definitive surgeries following DCS.

12.1.3.3 Acute Care

Appendectomies are critical interventions that will be required if an astronaut develops appendicitis during a mission [66]. There are two primary surgical techniques for performing an appendectomy: open surgery and laparoscopic surgery. Traditionally, open surgery was the standard approach, requiring an incision to access and remove the appendix. However, over the past few decades, laparoscopic surgery has become the preferred method for treating both nonperforated and perforated appendicitis due to its minimally invasive nature and associated benefits, such as reduced postoperative pain, shorter recovery times, and lower infection rates [66]. Similarly, cholecystitis, an inflammation of the gallbladder often caused by gallstones, requires surgical intervention to remove the gallbladder. This surgery can also be performed using either the open or laparoscopic approach [67]. The management of renal stones in space is also crucial. While small stones can often be passed naturally with the aid of muscle relaxant medications containing alpha-blockers, larger stones require more advanced interventions [68]. One non-invasive approach is extracorporeal shock wave lithotripsy, where high-energy sound waves are used to break down the stones into smaller fragments that can be excreted naturally in the urine. Ureteroscopy is routinely used to treat stones located in the bladder or lower ureters. This treatment involves introducing a small, flexible ureteroscope through the urethra and bladder to allow direct visualization and removal or fragmentation of the stone using specialized instruments. Percutaneous nephrolithotomy is a minimally invasive surgical alternative for larger stones found within the kidney.

12.2 Autonomous Robotics for Trauma and Emergency Care in Space

Autonomous robotic systems are poised to play a pivotal role in support of trauma and emergency care in long-duration space missions. At its core, a robotic system is a programmable machine engineered to automate tasks traditionally performed by humans. Over time, these systems have been augmented with various sensors, including vision devices like 2D and 3D cameras, accelerometers, inertial measurement units, proximity sensors, and force sensors. The most transformative development in robotics, however, has resulted from the integration of AI, which enabled three key components: perception, decision-making, and learning. Robots can now perceive their environment much like humans do, make informed decisions, and learn from past experiences to continuously improve their performance, thus growing into increasingly intelligent and autonomous systems. In the medical field, these systems transform into dynamic agents capable of working alongside healthcare providers. They can assist in clinical procedures, expand the operational capacity of medical professionals, and autonomously manage specific tasks within a surgical workflow [69].

In space, autonomous medical robotics can emerge as a particularly powerful tool. These systems have shown promise to enhance the accuracy, precision, and repeatability of healthcare delivery [70, 71]. These attributes are critical in environments where errors can have dire consequences, and managing health complications poses significant challenges. Autonomous robots can also improve clinical support by assessing injuries, providing diagnostics, and autonomously executing surgical interventions, either partially or in full. This capability is invaluable for optimizing the use of limited medical resources on a spacecraft and addressing extreme scenarios where healthcare providers may become unavailable. Furthermore, AI-powered robotics excel at adapting to new environments, continuously learning from each operation to improve their performance in future, unforeseen scenarios. This behavior is beneficial as we venture into the unknown realms of space, where the exact medical challenges are largely unknown.

Although commercial systems have achieved some level of autonomy, they still heavily rely on human input [69]. Deep space missions, with their extreme conditions and operational constraints, will demand more autonomous systems to ensure that medical care is delivered effectively and in a timely manner. Thus, the remainder of this chapter will look at the latest advancements in autonomous medical robotics research, with a particular emphasis on innovations that can be useful during space travel. Given the widespread use of AI in healthcare, our discussion will only include AI algorithms that support robotic system autonomy.

12.2.1 History of Medical Robotics in Space

Much of modern robotic surgery can be traced back to early NASA initiatives to promote space exploration [72]. In the 1970s, researchers at NASA's Ames Research

Center proposed providing medical support to astronauts in space via a robotic system operated by clinicians on Earth, a concept known as teleoperation [72]. Although the project remained unfunded for over a decade, it eventually gained the support of the US military, which recognized its potential for use on battlefields, environments similarly characterized by remoteness and austerity. When NASA researchers created the first prototype of a teleoperated robotic system, they rapidly recognized the limitations posed by time delays in space teleoperation [72]. This realization redirected research efforts toward shorter distance teleoperation, ultimately catalyzing the development of the first commercial surgical robotic systems, including AESOP, da Vinci, and Zeus [73]. Among these, the da Vinci Surgical System has been particularly transformative, utilized in over 11 million procedures worldwide since 2000, including 1.5 million surgeries in 2021 alone [74]. Following these pioneering systems, other robotic platforms have been effectively employed across a variety of surgical procedures, including minimally invasive biopsies, orthopedic surgery, radiosurgery, urological surgeries, cardiology interventions, and neurosurgery.

Despite years of scientific progress, robotic surgery in space has remained largely experimental and untested in actual missions. The first and only surgical robotic system to reach LEO is the Miniaturized In Vivo Robotic Assistant, known as spaceMIRA, developed by Virtual Incision and the University of Nebraska [75]. SpaceMIRA, a 2-pound device, builds on its Earth-bound predecessor, MIRA, which was created for colectomy procedures [76]. Unlike traditional teleoperated robotic systems, MIRA features two miniaturized robotic arms, one for grasping and one for cutting, that operate directly inside the patient's body through a single incision. In February 2024, MIRA received the de novo classification from the Food and Drug Administration as a table-mounted miniature electromechanical surgical system. SpaceMIRA was further miniaturized for space surgeries, reducing its overall length by about 3 inches compared to MIRA's. On February 22, 2024, spaceMIRA successfully carried out the first-ever simulated robotic surgery aboard the ISS. The study involved two types of experiments simulating surgery on rubber bands: one was a pre-programmed run for a semi-autonomous operation, and the other was a teleoperated session where a surgeon on Earth controlled the robot. While the outcomes of the semi-autonomous operation remain unpublished, reports indicate that during teleoperation, despite communication delays ranging from 0.6 to 0.8 s, the surgeon successfully cut through the rubber bands, thereby compensating for the delays using their expertise [75].

Despite the scarcity of space-based robotic surgery trials, significant progress is being made on Earth toward autonomous medical procedures and surgeries. These developments lay the groundwork for future space medicine and will be the focus of our next discussion.

12.2.2 State-of-the-Art Robotics for Trauma and Emergency Care

When an emergency patient is treated, the process starts with an assessment of vital signs such as heart rate (HR), blood pressure (BP), respiratory rate (RR), oxygen saturation (SpO_2), and body temperature (BT). This initial triage determines the severity of the patient's condition and identifies immediate threats. Following that, a diagnostic evaluation, including imaging and blood testing, is conducted to identify underlying issues. Based on these findings, interventional procedures, ranging from medication administration to surgery, are performed. We will thus divide our overview of autonomous medical robotics into three areas, each corresponding to these key steps in emergency medical treatment: initial assessment and triage, robotic diagnostic evaluation, and robotic interventional procedures, as illustrated in Fig. 12.1.

12.2.2.1 Initial Assessment and Triage

Vital signs are often measured using separate instruments like sphygmomanometers, thermometers, and pulse oximeters. Over the years, compact wearable devices have emerged for longitudinal and ambulatory vital sign monitoring, capable of measuring several physiological parameters with a single device [77]. US miniaturization led to the development of adhesive US patches the size of a postage stamp that can measure BP and even collect US images of organs like the lungs and heart [78]. While these wearables are useful for continuous health monitoring, they have drawbacks such as limited battery life, potential discomfort for the wearer, and susceptibility to damage from impact or wear and tear. As a result, remote photoplethysmography (rPPG) technology, which enables contactless measurement of patient vital signs, is becoming increasingly popular [79]. Clinically used for measuring SpO_2 and pulse rate, photoplethysmography (PPG) works by measuring the amount of light absorbed or reflected by human tissues using contact devices such as electronic pulse oximeters. Signal processing advances have enabled visual contactless physiological monitoring by consumer RGB cameras that extract PPG signals from facial or abdominal skin [80]. Once the PPG signal is obtained, deep learning can be used to estimate vital signs such as HR [81, 82], BP [81, 83], RR [81, 84], and SpO_2 [82] with an accuracy comparable to that of standard contact devices [84–86]. Although most of these algorithms are designed to extract a single vital sign from the PPG signal at a time, the development of large-scale, multi-task AI models capable of estimating multiple vital signals simultaneously has been deemed feasible [80]. In addition to rPPG-based vitals monitoring, thermal imaging using infrared (IR) signals can detect body temperature and help localize wounds from active bleeding, which is particularly useful in trauma cases [87]. Dual RGB/thermal cameras, such as the Teledyne FLIR Hadron 320, can facilitate comprehensive care in space, where minimizing the number of devices is critical.

Most rPPG algorithms were evaluated on high-quality video data collected in controlled environments [80, 84] In real-world emergencies, it is impossible to maintain consistent and continuous visual access to the patient's skin from a single location. Mounting cameras and sensors on mobile robots offers a dynamic

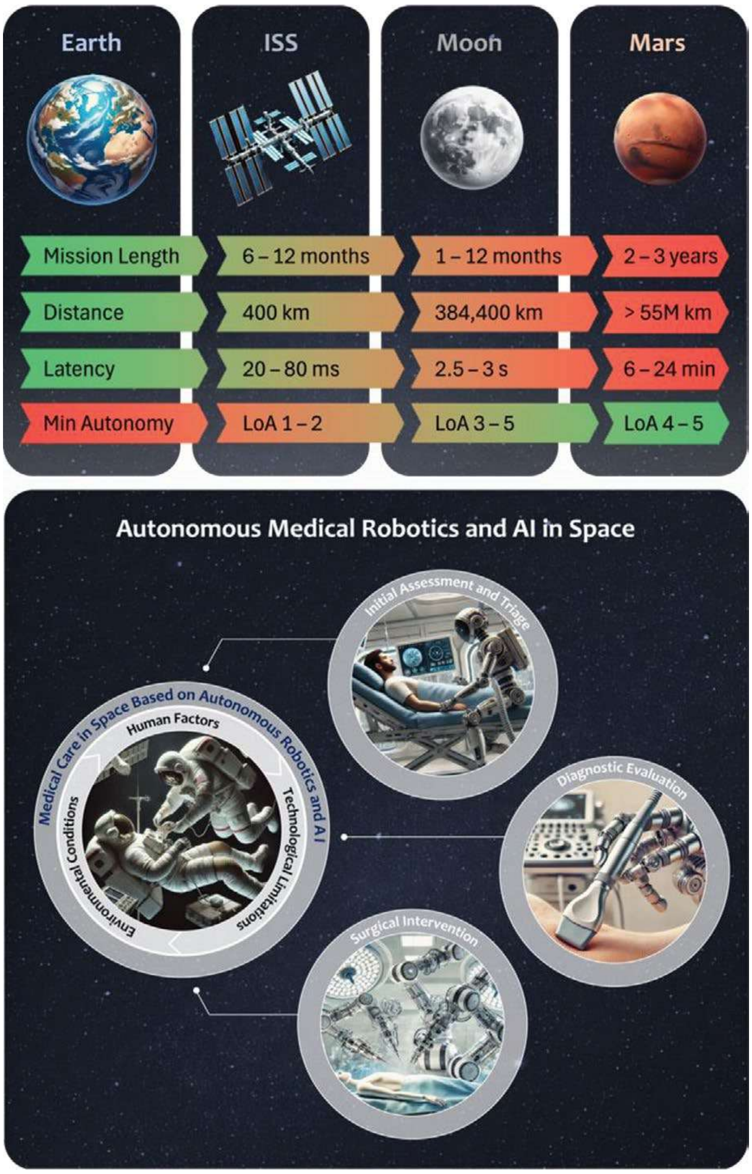

Fig. 12.1 The figure illustrates the relationship between increasing distance from Earth to the ISS, the Moon, and Mars. As missions venture farther from Earth, the length of the mission extends, communication delays increase, and the need for highly autonomous robotic systems becomes critical. These systems are pivotal in addressing the three major challenges in space medicine by: (1) performing initial assessment and triage, (2) conducting diagnostic evaluations, and (3) executing surgical interventions, thereby ensuring the health and safety of crew members in deep space exploration missions. (AI generated image created with OpenAI Inc., DALL-E 3, 2024)

platform for improved patient access. During the COVID-19 pandemic, Huang et al. developed a quadruped robotic system for contactless vital signs monitoring in hospitals [88]. The system uses IR and multimonochrome cameras to automatically track individuals and measure skin temperature, HR, and RR, while also screening for fever, tachypnea, and tachycardia. Mobile quadruped robots have been a popular platform for collecting patient data in hospitals and public spaces [89, 90], as well as in more challenging settings like rescue missions [91]. Similarly, drones have been experimentally deployed to accident sites to autonomously assess a subject's vital signs and identify life-threatening wounds [92]. Advanced algorithms for skin segmentation [93], object tracking [94], and robot motion planning [95] facilitate capturing high-quality patient video data using visual servoing. This technique ensures that the best skin area remains in the robot's field of view long enough to reliably extract vital signs. In space, mounting cameras on mobile robotic platforms or manipulators can help autonomously collect critical data for patient triage.

Machine-learning algorithms, including logistic regression, random forests, and deep learning, have been developed to streamline patient triage by predicting the likelihood of acute outcomes in emergency scenarios [96]. Input for these models often includes vital signs, medical history, and primary complaints [97]. Studies have shown that such “electronic” triage accurately classifies emergency severity index level 3 patients and highlights opportunities for using predictive analytics to support early triage decisions [98]. Building on mobile robots’ ability to collect contact-free vital signs in space, predictive triage can augment the attending provider’s capacity by assisting with critical decision-making and giving them more time to prepare for urgent surgical procedures.

12.2.2.2 Robotic Diagnostic Evaluation

If the patient’s vital signs are stable, medical imaging is employed next to assess the severity of the injury and diagnose the patient’s condition. US is the primary medical imaging modality used on the ISS due to its lightweight, compact design, and low power requirements. It is also used in the primary assessment of trauma patients in search of abdominal hemorrhaging via the extended Focused Assessment with Sonography for Trauma (eFAST) exam. Currently, all US scanning procedures on the ISS are manually performed by the crew members themselves, guided remotely by a physician on Earth [99]. Attaching a US probe to a robotic arm is the most intuitive approach for enabling autonomous robotic US scanning.

First, the robotic system must identify the patient’s body via 2D and 3D cameras. Before attempting to collect US images of the abdomen, the robot must locate scannable skin, which entails differentiating healthy skin from wounds, bandages, and clothing. Solutions specific to abdominal skin segmentation were proposed using a UNet network [100], alongside more advanced algorithms for generic skin segmentation [93]. Wound delineation has also been investigated [101, 102], as has clothing segmentation from colored images [103]. While most of these algorithms have not yet been integrated or tested specifically on trauma patients, deep learning’s current capabilities should be sufficient for these applications, given access to adequate training data. Another method of interest involves using body surface information to infer key internal organ markers, such as the femoral artery bifurcation point or the center of the femoral head. Siemens Healthineers developed a convolutional neural network that can generate a patient-specific avatar model (DARWIN) from a depth camera snapshot [104]. This patient model was used to map a relationship between the body’s surface geometry and select 3D internal anatomical markers with high accuracy [105, 106]. A total of 60 predicted markers on the rib cage, for example, had a mean Euclidean error of 14.8 mm [107]. These internal landmarks can be used to avoid imaging certain areas under US or to help the robot locate specific organs, including the liver, spleen, and femoral artery. Researchers have also developed methods to estimate a patient’s pose in real time [108] and predict eFAST locations on a patient’s body [108, 109].

Several robotic systems have been developed for teleoperated abdominal US scanning [109–111], with more recent work focusing on autonomous operation to decrease the dependency on operator skills and availability. A team at Johns Hopkins

University demonstrated preliminary feasibility of autonomous point-of-care US scanning for lung diagnosis and staging, with and without pre-operative patient CT data. Their system comprises a 3D RGB camera, a force sensor, and a wireless US probe, mounted on a six-degrees-of-freedom robotic manipulator [106]. To avoid obstruction of US images by ribs, the internal markers prediction algorithm [105] was used to estimate landmarks on the ribcage using only surface body scans. A study on a full torso US phantom [112] showed that using only the predicted landmarks and force feedback, 87.5% of autonomously acquired US images without preliminary CT data were interpretable. Other studies have reported successful autonomous robotic US scanning of solid abdominal organs such as the liver [113] and vascular structures like the jugular artery [114]. Raina et al. proposed a solution that uses demonstrations from expert sonographers to train robots to acquire high-quality US scans [115]. The team used Bayesian optimization with domain expertise to predict and scan regions where US images are of the best quality. Experiments on urinary bladder phantoms showed an accuracy of 98.7% in probe positioning and 97.8% in force application [115]. Others have also explored advanced learning frameworks for autonomous robotic US manipulation, such as imitation learning and reinforcement learning [116, 117]. These various learning frameworks have both advantages and disadvantages, which will be discussed in the following sections.

Although eFAST is an effective tool for detecting pneumothorax and free fluid in abdominal cavities, patients with positive scans typically undergo CT imaging to assess hemorrhage volume and classify trauma severity. Given that the miniaturization of CT scanners for space applications is still in the experimental phase [118], robotic US scanning combined with US image analysis can be a valuable diagnostic alternative. Most current algorithms concentrate on the binary identification of abdominal free fluid [119] or pneumothorax [120] in US images. Some US segmentation models exist for delineating organs such as the liver [121], heart compartments [122], and blood vessels [123], but they are limited in number primarily due to the scarcity of labeled US datasets. To address this, US data simulation from 3D imaging modalities was proposed [124]. State-of-the-art deep learning models, capable of identifying over 100 different organs from CT [125] and MRI data [126], can help generate extensive datasets of high-quality annotated US images. These datasets can be leveraged to develop more sophisticated US segmentation algorithms [127, 128], enable volumetric interpretation of US data [127, 128], and train robots to dynamically adjust probe placement based on US image analysis [129]. Moreover, novel multi-modal registration techniques [130] can integrate astronauts' pre-existing medical imaging data with intraoperative images, further enhancing the accuracy and precision of autonomous robotic diagnostic procedures in space.

12.2.2.3 Robotic Interventional Procedures

Levels of Robotic Autonomy Innovations driven by research in AI have gradually increased robotic autonomy in various surgical tasks. Autonomous features in surgical robotics have shown superior performance compared to expert surgeons in both synthetic and living tissues [131]. Some of these features are already integrated into clinically approved surgical systems. However, robotic autonomy encompasses a broad spectrum, ranging from entirely teleoperated systems to autonomous "robotic surgeons" that require no human supervision [132]. Over the years, the definition of the different levels of autonomy has been refined to include a formal framework based on four cognition-related functions of a system: generating an option, executing an option, monitoring an option, and selecting an option from many [133]. The number and type of these functions performed by the robot help classify the system into a specific level of autonomy [134].

To this end, the standard classification for surgical robotics currently comprises five levels of autonomy [132, 134]. At Level 0, robots operate as tools controlled entirely by humans, such as teleoperated robots and prosthetic devices that respond directly to user commands. The Intuitive da Vinci system exhibits Level 0 autonomy, utilizing "transparent" teleoperation, where the surgeon's movements on the control interface are exactly replicated by the surgical instruments on the patient side [135]. At Level 1, robots provide cognitive and physical assistance, offering mechanical guidance or support while the human operator maintains continuous control. Examples include surgical robots with virtual fixtures and haptic feedback, such as MAKO by Stryker and ROSA ONE by Zimmer Biomet for knee arthroplasty. Level 2 robots achieve task autonomy, performing specific tasks initiated by a human with discrete control, such as robotic surgical suturing. Examples of such systems include the Senhance robot by Asensus Surgical for laparoscopic procedures and the CorPath GRX by Corindus for percutaneous coronary interventions and vascular procedures. Level 3, or conditional autonomy, allows robots to generate and adjust task strategies during execution, requiring human approval for strategy selection but performing tasks with minimal oversight. As of 2024, the only robotic systems to achieve Level 3 autonomy and receive the FDA's 510(k) clearance are the iSR'obot Mona Lisa 2.0 (Biobot), TSolution One (Think Surgical), and ARTAS iX System (Venus Concept). At Level 4, robots exhibit high autonomy, making medical decisions and executing complex procedures under the supervision of a qualified healthcare professional. Finally, Level 5 represents full autonomy, where robots can perform entire surgeries independently, making all necessary medical decisions without any human intervention. To date, no commercially available surgical systems have reached Levels 4 or 5 autonomy. However, these advanced levels are actively being researched at various institutions, which we will discuss next.

Autonomous Surgical Robotics The Veebot system (Veebot LLC) is a Level 4 autonomous robot designed for vascular access [136]. The procedure begins by positioning the patient's arm through an archway over a padded surface, followed by constricting the arm using an inflatable cuff to enhance vein visibility. The system then employs infrared (IR) light to illuminate the inner elbow, and software algorithms compare the camera's view against a vascular anatomy model to select the optimal vein for puncture. US imaging then confirms the selected vein's location and suitability. A robotic arm aligns the needle with the vein and performs the insertion, completing the procedure within approximately one minute. Human intervention is limited to attaching appropriate collection tubes or intravenous bags to the syringe. While this system is not yet commercially available, it has demonstrated successful cannulation in 83% of veins [137]. Chen et al. developed a comparable robotic phlebotomy device [138]. Their system combines near-IR and US imaging to create a 3D model of the patient's vasculature and uses miniaturized robotics for precise needle placement. The platform was later augmented by adding a sample handling station and a centrifuge-based blood analyzer, enabling fully automated, point-of-care diagnostic blood testing on-site [139]. The current iteration of this system supports a 3-part white blood cell differential and hemoglobin measurement. While initially conceived for blood sample collection, these autonomous systems have potential applications beyond phlebotomy, including critical care interventions such as the placement of REBOA for patient stabilization [140].

Recent research focuses on advancing autonomous robots with Level 3 autonomy and higher for surgical tasks such as suturing and tumor removal. The Smart Tissue Autonomous Robot (STAR) is one research platform that uses machine learning for tissue tracking to autonomously complete small bowel anastomosis [131, 141]. STAR consists of a suturing tool, an imaging system that combines near-IR and 3D plenoptic imaging, and supervised-autonomy control. A comparative study evaluating the efficiency and efficacy of STAR against state-of-the-art master-follower robotic (da Vinci) and manual laparoscopic techniques demonstrated remarkable improvements. STAR achieved a five-fold and nine-fold reduction in operation time compared to robotic and manual techniques, respectively, while exhibiting four times greater consistency in suturing planar phantoms with one knot and nine running sutures [141]. Moreover, STAR pioneered pre-clinical supervised autonomous robotic anastomosis of porcine small intestines in both open and laparoscopic surgeries, outperforming expert surgeons' manual and robotically assisted surgery in terms of consistency and accuracy [131]. Concurrently, the Autonomous System for Tumor Resection (ASTR) has been developed for supervised autonomous tumor excision [142]. ASTR consists of two robotic manipulators, one equipped with an electrosurgical instrument and the other with a vacuum grasping tool. ASTR also employs a dual-camera vision system to detect color inks and near-IR fluorescent markers used to delineate tumor margins. The robot autonomously plans and executes trajectories to excise a tumor. Using glossectomy as a case study, ASTR successfully performed six consecutive supervised autonomous pseudotumor resections on ex vivo porcine tongues without positive tumor margins, with an accuracy comparable to manual pseudotumor glossectomy performed by an experienced otolaryngologist. Current research is exploring the system's generalizability to partial nephrectomy procedures [143].

While the STAR and ASTR systems represent significant advancements in autonomous surgical robotics, they rely on physical tissue markers to guide their operations [131, 142]. Although effective for certain tasks, these methods cannot be used for all actions in surgical procedures, such as tissue manipulation and knot tying, which are challenging to reduce to a set of motion primitives and require dynamic adaptability to the environment. The broader field of robotics has greatly benefited from learning frameworks that enable robots to "learn" through two primary approaches: reinforcement learning (RL) and imitation learning (IL). RL is a framework where the robot teaches itself certain actions by directly interacting with an environment, while IL enables the robot to mimic expert behavior without the trial-and-error exploration that is characteristic of RL. These approaches have gained popularity in tasks such as walking, grasping, and tabletop object manipulation by industrial robots [144, 145]. Surgical tasks, however, present unique challenges that demand more precise and delicate manipulation of deformable soft tissues, coupled with the need to overcome perceptual difficulties caused by occlusions and inconsistent lighting. Despite the relatively recent application of RL and IL in surgical robotics, progress has been promising. Recent research has demonstrated the successful application of combined RL and IL for automatic laparoscope motion control, trained on a 3D-rendered surgical scene derived from real-world collected surgical videos [146]. The learned robot policy for laparoscope control was shown to outperform baseline IL approaches and generalize well to unseen environments. Scheikl et al. adopted IL to perform gentle manipulation of deformable objects while requiring fewer demonstrations, addressing a common challenge with these algorithms [147]. Their approach was successfully tested in a real-world task on a porcine liver with an attached latex gallbladder, where one laparoscopic robotic instrument learned to manipulate the gallbladder to expose a target point, which was then autonomously touched by a second laparoscopic robotic instrument [147]. In another study, Kim et al. demonstrated IL's capabilities in training a da Vinci system using 3D colored videos and the robot's kinematics data to autonomously perform surgical tasks that include lifting soft tissue, picking up and transferring a needle between two surgical tools, and tying knots [148]. The system's generalizability was successfully validated on both phantoms and ex vivo animal tissues that were not used in training.

12.2.3 Future Technological Directions

Despite promising results, certain technological advancements are necessary to make these robotic systems viable for providing autonomous care in space, particularly addressing the unique challenges outlined at the beginning of this chapter. A major issue in autonomous surgical robotics is the ability to extrapolate to environments that were not seen in training. This concern is amplified in space applications, where both patient physiology and tissue behavior differ substantially from terrestrial norms, and relevant data is scarce. While developing algorithms with enhanced extrapolation capabilities is essential, it remains insufficient without comprehensive validation. A promising solution lies in a dual approach: generating high-fidelity simulated data that closely approximates real-world scenarios while simultaneously advancing learning algorithms to enhance the generalizability from simulated environments to real conditions. This approach necessitates advanced augmentation techniques beyond simple rotation, scaling, and flipping to maximize the utility of limited real-world surgical data. Deep networks, such as generative adversarial networks, should be further improved to synthesize realistic surgical scenes, while style transfer techniques can be adapted to represent more diverse surgical conditions and patient anatomies. Researchers would thus be able to leverage a limited number of surgical videos recorded in microgravity to generate novel, stylistically consistent simulations based on terrestrial surgical procedures. These artificial demonstrations can in turn be utilized to train robotic systems using IL, with the development of advanced methods to ensure effective generalization from simulated to real-world data. Such methodology does present some caveats, however. In IL, a policy—defined as a strategy that maps observations to actions—guides the robot's behavior. Robots are penalized during training if their execution diverges from the expert's demonstrations. A critical consideration is that artificial data may not consistently provide optimal expert demonstrations. This limitation is further compounded by the fact that robotic systems, with their unique mechanical designs and dynamics, may achieve task optimality differently from human experts. For instance, a robotic arm, with its increased degrees of freedom, can manipulate surgical tools in ways that exceed human anatomical capabilities. Additionally, altered gravitational conditions might necessitate modified kinematic strategies to execute a surgical task. Delving into the mathematical foundations of IL-based frameworks becomes essential to estimate better policies that can effectively balance the importance of task outcomes with the accuracy of behavior imitation. A key advantage in advancing IL is the potential to learn from not only manual expert demonstrations but also teleoperated robotic interventions, rendering the learning process more intuitive and organic for a robot.

An alternative approach for artificial data generation is to utilize realistic simulation platforms that employ physics laws and AI to create virtual representations of the real world, rather than relying on prior surgical videos. Current simulators, constrained by simplifying assumptions, struggle to model the complex, non-linear behaviors of biological tissues. Future research should focus on enhancing the fidelity of soft tissue deformation, cutting, and suturing simulations, incorporating factors such as anisotropy, viscoelasticity, and patient-specific variations. For space surgery simulations, microgravity-induced physical dynamics must also be accounted for. Additionally, improving photorealism is crucial, as visually unconvincing training data will hinder a robot's ability to generalize to real-world scenarios. In surgical robotics, enhanced simulations can be leveraged to train RL-based algorithms, addressing the persistent "sim-to-real" gap where performance in simulated environments often fails to translate effectively to real-world clinical scenarios. To further bridge this gap, domain adaptation methods that align feature distributions between simulated and real data, combined with progressive neural networks for sequential task learning, offer promising solutions. Meta-learning algorithms for quick task adaptation can enhance the generalizability of surgical robotic solutions. Developing hybrid sim-to-real training pipelines, where robots are initially trained in simulation and fine-tuned on limited real-world data, can also be adopted. Even though utilizing simulation to reliably train robots for real-world surgeries will be quite difficult, improvements in simulations can still be leveraged to aid the robot in decision-making tasks, for instance, by predicting future tissue state and interaction with surgical tools. Online learning algorithms capable of updating tissue models in real time during surgical procedures are valuable for immediate adaptation to patient-specific variations and unexpected scenarios. Realistic simulations also show tremendous potential to improve the medical preparedness of CMOs. Advanced VR environments that emulate space conditions can become particularly powerful platforms for medical training on Earth itself. Enhancing VR immersiveness with realistic tactile feedback will enable CMOs to practice for medical procedures as if they were operating under microgravity and physical constraints, while also preparing them psychologically for the distinct challenges of providing care in the demanding environment of space.

The constraints of spacecraft transportation necessitate innovative design solutions for medical equipment and robotic systems. Miniaturization emerges as a paramount consideration, not only reducing the invasiveness of surgical procedures but also enabling novel interventions while potentially lowering power requirements. Concurrently, the exploration of lightweight yet robust materials for robotic components and surgical tools is crucial. Developing modular robotic designs capable of accommodating various medical instruments can maximize system versatility in the resource-limited confines of a spacecraft. Advancements in additive manufacturing, particularly in rapid production capabilities and multi-material printing, present transformative possibilities for on-demand fabrication of surgical tools, robot replacement parts, and patient-specific devices. This approach, guided by optimized design algorithms, could significantly enhance the autonomy of space-based medical care. Equally critical is the integration of novel sensing technologies to provide rich, multi-modal information about the surgical field, addressing the unique challenges posed by microgravity environments. Miniaturized force sensors, multi-modal cameras, and spectroscopic sensors can offer unprecedented insight into tissue properties and composition. The integration of flexible and stretchable electronic sensors into surgical instruments or artificial tissues represents a frontier in sensory feedback. The true value lies not only in the development of these advanced technologies but also in the integration of sophisticated algorithms capable of efficiently fusing and interpreting multi-modal data streams in real time, thereby enabling more informed and precise surgical interventions.

12.3 Conclusions

The integration of autonomous robotics and AI into space-based trauma and emergency care represents a paradigm shift in medical capabilities for future space missions. The unique challenges of space environments—microgravity, isolation, and limited resources—necessitate innovative solutions that enhance robotic autonomy and decision-making capabilities. Communication delays and limited availability of trained personnel necessitate real-time analysis and adaptive responses to medical emergencies. As we advance toward longer and more complex space missions, ensuring astronaut health and safety through autonomous medical interventions will be paramount. Current technological progress offers potential solutions, but the isolation of space missions demands extensive redundancy and fail-safe features to ensure reliable operation. This raises important questions about liability and decision-making authority in critical situations, highlighting the need for developing clear regulatory guidelines and protocols. Collaboration between space agencies, medical institutions, and technology developers will be crucial in addressing remaining technical, ethical, and legal challenges.

Autonomous medical robotics and AI not only promise to revolutionize space exploration but also offer transformative insights for medical care on Earth, potentially improving healthcare delivery in remote or resource-limited settings. The development of autonomous medical robotics for space applications represents a frontier of innovation with far-reaching implications. As we continue to push the boundaries of human space exploration, balancing technological innovation with ethical considerations will be essential to ensure these increasingly autonomous systems remain aligned with human values and medical best practices. The journey toward fully autonomous medical care in space is complex and challenging, but its potential benefits for both space exploration and terrestrial healthcare make it a pursuit of utmost importance and promise.

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