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Rescue Robots for the Urban Earthquake Environment

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Abstract

Robotics have important applications in the field of disaster medical rescue. The deployment of urban rescue robots at the earthquake site can help shorten response time, improve rescue efficiency and keep rescue personnel away from danger. This discussion introduces the performance of some robots in actual rescue scenarios, focuses on the current research status of robots that can provide medical assistance, and analyzes the merits and shortcomings of each system. Based on existing studies, the limitations and development directions of urban rescue robots are also discussed.

An earthquake disaster is destructive and will cause a large number of casualties. Secondary disasters such as aftershocks and mudslides are often caused by earthquakes, making it difficult to deploy disaster medical assistance teams (DMATs).[1] The main challenges of rescuing survivors after an earthquake include the following: (1) time-consuming survivor location; (2) constrained manpower; and (3) unsafe evacuation of victims.[2]

To solve these problems, the concept of robotic urban search and rescue (USAR) has been put forward in the past century. A variety of dexterous mobile robots can be deployed to locate victims and transfer them to a safe place in dangerous environments. Theoretical research has been mature in the field of search robotics, including robot motion control systems and path planning algorithms, etc.[3,4] Over the years, different types of USAR robots have been developed and applied in many real disaster sites. After the 2001 World Trade Center attack, USAR robots participated in rescue tasks.[5] During the 2011 earthquake in Japan, mobile robots carried out the inspection task in damaged buildings.[6] In contrast, there are few cases of robots used for medical rescue after finding survivors. It seems that directly providing medical assistance or autonomously evacuating the wounded is beyond state-of-the-art robotics. This discussion reviews cases where rescue robots have been used and novel studies on robot systems that directly contact the wounded. The purpose is to analyze limitations and discuss future developments.

Urban Search Robots

As a scout for postdisaster rescue work, urban search robots usually perform simple and crucial tasks, including obtaining terrain information and locating survivors in confined spaces and collapsed buildings that are not possible or safe for people to access. It is applicable for search robots to collect dangerous material samples during investigations in chemical factories or warehouses. Although most of the robots discussed below are also called "search-and-rescue robots" in many studies, they do not provide medical assistance to the wounded. In general, search robots do not make physical contact with survivors.[7–22]

The common robotic platform Quince has a deformable crawler structure, which can autonomously adjust to unstructured terrains with the application of semi-autonomous control algorithms.[7] Due to the modular interoperability and extensive hardware and software architecture, the robot is versatile. After the Eastern Japan earthquake in 2011, Quince was modified and deployed to collect information, including radiation levels in the damaged buildings of the Fukushima nuclear power plant.[8,9] NIFTi (Natural Human-Robot Cooperation in Dynamic Environments) deployed multiple types of robots to assess damage to local historical buildings and cultural artifacts in the red area of Mirandola of the Emilia-Romagna region after 2 major earthquakes and several severe aftershocks in northern Italy in 2012.[10] Subsequently, the Long-Term Human-Robot Teaming for Disaster Response (TRAD) project inherited the development of the NIFTi project and continued to develop the USAR robot.[11] In 2016, a TRAD project deployed search robots to provide 3-dimensional textured models of the interior and exterior of 2 severely damaged medieval churches after the 6.2-magnitude earthquake in Amatrice, Italy.[12] A hyper-redundant serial-linkage snake robot called the Unified Snake was designed by a team at the Carnegie Mellon University Biorobotics Laboratory (Pittsburgh, PA) in 2012.[13] The robot

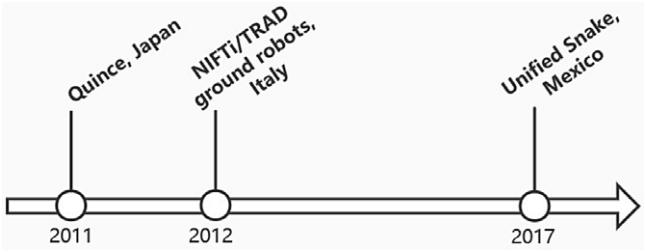


Figure 1. Timeline of implementation of robots.

consisted of multiple sturdy, closed modules. Each module weighed approximately 0.16 kg and produced a torque output of 1.3 Nm. The team improved the gait control of the robot and added new functions in different modules in further research.[14,15] In the wake of the 2017 earthquake, the Biorobotics team assisted Red Cross rescue workers in the USAR efforts in collapsed buildings in Mexico City.[16] A timeline of the implementation of these urban search robots is shown in Figure 1. Some other robotic platform studies have made progress, but they have no field application experience.[17–20] In addition to ground robots, unmanned aerial vehicles based on robot vision have provided better options for improving disaster response efficiency, and amphibious robots for amphibious and aerial environments have also had good application prospects over the past few years.[21,22]

Field Diagnosis Robots

Once a survivor has been found, the next step is usually to determine their vital signs, and assess to determine if life-saving interventions are indicated and then to extract the patient to begin the safe evacuation and transportation process.[23] The robot system can be used to assist medical personnel in the initial diagnosis of survivors efficiently at the scene of the injury. The development direction of field diagnosis robots is to integrate them with urban search robots or evacuation robots that will be introduced later. This area is less mature than urban search robots.

For patients with internal hemorrhage, a common injury after an earthquake, rapid screening/triage should be prioritized.[24,25] FASTele, a wearable tele-echography robot system developed by Ito et al. in 2010, was a solution.[26] The system enabled focused assessment with sonography for trauma (FAST) at the injury site. The robot was attached to the patient's body, and an echo probe of the robot was placed in a rough position of the FAST area by a bystander. Then, the position was fine-tuned by a doctor remotely. In the experiments with some examinees and doctors, the mechanism was confirmed to be effective. There was no deterioration in the echo images, and a diagnosis was possible even with body movement. The doctor could complete the remote FAST in approximately 6 min. This new diagnosis flow using the robot system did not delay transportation. As a result, the robot system has the potential to improve the survival rate of traumatic shock patients. In addition, it is indicated that FASTele still has FAST performance under vehicle vibration conditions.[27] An automatic internal bleeding detection robot system based on ultrasound (US) image processing was constructed to improve the sensitivity.[28,29] The boundary of the organ (liver and kidney) and internal bleeding were determined using low-brightness set analysis. However, failure of segmentation and detection might occur when the extracted organ area is too small in the image. In the future, the team will improve some methods to enhance the performance of the system and enable the robot to be extended to the diagnosis of all FAST areas. Although FASTele is not a mobile robot, and it takes much more time to attach the robot to the overweight, this robot system is still a notable attempt.

A semiautonomous rough terrain rescue robot named Tehzeeb was presented by Suthakorn et al.[30] Subsequently, based on the previous research foundation, the team added a victim detection system to the mobile robot platform and proposed a rescue robot named Tele-Operation that can identify victims through heat sensors.[31] In 2014, the upgraded robot Tele-Operation IV (Fourth Generation) was deployed to participate in the rescue operation of collapsed buildings in the Pathumthani Province, Thailand.[32] The robot system was equipped with a camera, microphone, noncontact temperature sensor, and carbon dioxide sensor to analyze victims information.

Evacuation Robots

Generally, DMATs deploy evacuation robots to extricate victims because of the shortage of manpower and the complex situation at earthquake sites. Sometimes 2 different robots are deployed to perform extraction and evacuation tasks. Using robots to extract the wounded involves a complex human-computer interaction process. The most important problem is maintaining the stability of the robot system during rescue and avoiding causing secondary injuries to survivors who were injured.

The Battlefield Extraction Assist Robot (BEAR) manufactured by Vecna® Robotics Inc. (Waltham, MA) is a typical kind of evacuation robot.[33] The mobile robotic platform has an anthropomorphic torso and leg-like deformable track structure. The injured person can be easily lifted from the ground and safely transported through a hydraulically powered articulated arm. The robot evacuation process is effective. The hydraulic system with pressure sensors prevents the extracted patient from secondary injury. As a 2-armed robot, it is suitable for extracting conscious people whose limbs are not severely damaged. However, the neck of the injured person is not supported, and the head is naturally drooping during transportation. Therefore, it is unreliable for BEAR to rescue a survivor who suffers from head trauma.

For fracture injuries, which are the most common in urban earthquakes,[34–38] immobilization or fracture support is necessary in the field. The novel tracked rescue robot Semi-Autonomous Victim Extraction Robot (SAVER), designed by a team at the Robotics and Mechatronics Lab at Virginia Tech (Blacksburg, VA), uses a tilted stretcher to load the wounded in the cabin of the robot.[39] After locating and driving up to the survivor autonomously,[40] the SAVER can estimate and adjust his posture through the Highly Dexterous Manipulation System (HDMS) manipulator system (developed by RE$^{2®}$ Inc.) to make extraction easier. Next, the support system slides down the stretcher and stabilizes the head and neck of the survivor.[41] The injured person is slowly pulled onto the declined stretcher by the shoulder grip system and evacuated to the casualty collection area. SAVER can protect the head and neck of the wounded when handling them, thereby avoiding secondary injuries. Because the remote operator controls the robotic arm to manipulate the injured person, the robot system requires a more intuitive robot-operator interface and lower communication delays to provide real-time feedback.

Crush syndrome (CS) is another leading cause of death for patients in earthquakes.[42] DMATs may treat CS but cannot perform dialysis because of the aftershocks.[43] To solve the safety problem, a rescue robot for evacuating patients with CS has been

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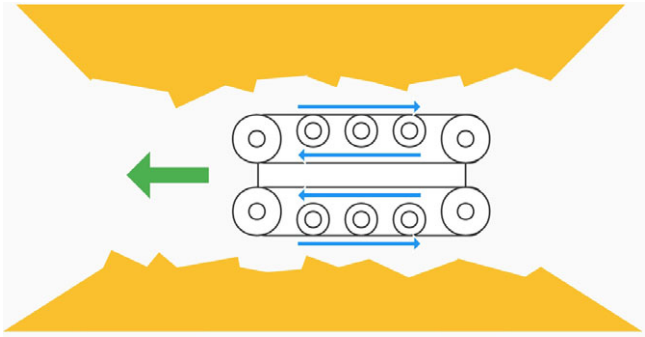


Figure 2. The crawler system of the rescue robot.

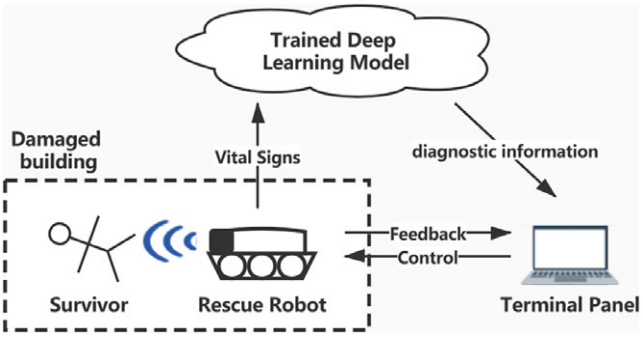


Figure 3. Conceptual architecture of rescue robot with CAD system.

presented.[44] The robot can proceed through narrow spaces and work under rubble with the dual-tiered crawler that runs in adverse directions. Figure 2 shows the crawler system. In addition to the vital sign sensor probe, including a near-infrared camera, infrared LED (light-emitting diode) light, and microphone, the robot is equipped with a crush syndrome prevention system. After the robot removes the rubble, affected parts of survivors are tightened smoothly by a pressure cuff to prevent reperfusion injury. Notably, this method is only a first aid treatment. Then, the victim is picked up in the container inside the robot body and returned to the ground for meticulous treatment. This robot still leaves some drawbacks. First, the robot cannot communicate wirelessly. The robot and the terminal control panel are connected by a 10-meter-long cable wire to transmit data and provide power, which limits the range of movement. Second, the robot needs a cable management assistant while it is working. Beyond the initial report, no further work was performed.

Limitations of Deploying Robots for Urban Search and Rescue

The main problems for urban search robots are insufficient information processing capabilities and complex robot operations. The robot operator suffered from cognitive overload in the rescue case of Italy.[10] The data given by the robot were not intuitive, which means that much information still needs to be handled by people. A similar problem also appeared in the robot-assisted rescue case in Mexico City in 2017.[16] As a consequence, the rescue personnel with minimal training could not replace the researcher to control the robot effectively on site. The nonsharing of data between robots is another problem. When multiple robots were working simultaneously, their collaboration performance did not meet expectations.

The most serious challenge for field diagnosis robots and evacuation robots is the safety of the injured in the human-robot interaction.[45] The robot can easily cause bruising (internal bleeding) on the contact parts of the human body, especially the extremities.[46] Almost all evacuation robots mentioned above have only been tested in a simulated environment, but the real postearthquake environment will be much worse. It is still impossible for these robots to ensure absolute safety in tests. According to the results of some studies, victims are more willing to believe in the actions of a robot than a human in an emergency scenario.[47,48] However, it was proposed that once robot errors occurred, they would lead to the destruction of the human-robot trust relationship, which is disastrous for the rescue robot.[49] Similarly, robot ethics and operational liability also need to be addressed. According to the current law, when rescue robots participate in operations, it is difficult to clarify the responsibilities of all relevant personnel, including technicians, decision-makers, operators, and doctors.[44] These factors limit the experiments of evacuation robots in real post-earthquake environments.

Determining an appropriate benchmark for urban rescue robots is another issue. The development teams from different countries test their robot systems in different environments, which makes it impossible to compare the results based on their reports. Robot competitions, including the European Land Robot Trail (ELROB), euRathlon, RoboCup Rescue, etc., seem to be the benchmark for robot systems.[50–53] There are still problems with this kind of competition for USAR robots. The participating teams mainly focus on the following tasks: (1) exploring buildings and mapping[51]; (2) interacting with facilities in the environment (such as valves)[52]; (3) finding and transporting trapped people (dummies).[53] In other words, these competitions focus more on "Search" but not "Rescue." Most of the participants used the manipulator to grab the dummy and even dragged it with a hook,[53] which would not be acceptable in a real-life scenario.

Future Directions

The development of emerging technology provides the probability of improving urban rescue robots. Based on deep learning, big data, and the latest fifth-generation (5G) wireless systems, remote computer-aided diagnosis (CAD) has become a novel direction. In theory, CAD systems will play a significant role in assisting physicians in making objective and effective diagnostic decisions.[54] After dealing with massive clinical data, CAD systems can emulate the diagnostic decision-making process of medical experts in the experiment.[55] Benefitting from a variety of deep learning models, CAD systems use feedback mechanisms to continuously improve their performance. Furthermore, the application of the 5G technique dramatically improves the data transmission rate and reduces the communication delay, which is an important guarantee for real-time telediagnosis. Current practices of telemedicine have been carried out in the clinical environment, including surgical consultations and multidisciplinary trauma care.[56] However, this field is still in its infancy, and the lack of objective and comprehensive results in the reviewed trials makes it difficult to draw conclusions related to effectiveness. Figure 3 shows a simple conceptual architecture of a rescue robot with a CAD system.

A brain computer interface (BCI) is an innovative form of interaction between humans and machines. In general, BCI takes an electroencephalogram (EEG) signal as input and controls external devices directly.[57] BCI does not rely on any muscle or

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neuromuscular pathway in communication. Thus, this technology was first used in assistive devices to help paralyzed but conscious patients recover and improve their quality of life.[58] The latest studies show that BCI also has promising prospects in nonmedical applications, such as user-state monitoring and collaborative robots at construction sites.[59,60] The currently tested BCI-based system can control robots with high accuracy. By enhancing robot control and improving safety, BCI-based systems are expected to become a new solution in human-dominated environments.

Conclusions

Reasonable deployment of urban rescue robots in earthquake scenarios can help shorten response-time and transportation-time, thereby decreasing the odds of mortality. Owing to all-terrain adaptability and environmental interaction capabilities, search robots have become an important part of DMATs. Studies of field diagnosis robots and evacuation robots have also shown promising results. Different robots are designed according to medical methods to deal with different injuries, including internal hemorrhage, fractures, CS, etc. However, robot systems that have direct contact with the wounded face the challenge of human-robot interaction security, and their performance in real-life scenarios is unknown. It is still necessary to test rescue robots in a more realistic simulated disaster environment. To meet the requirements of collaboration between multiple robots and human-robot cooperation, improving data sharing capabilities and machine intelligence is 1 of the focuses of future research. Artificial intelligence-based CAD systems and BCI-based control systems are also promising development directions.

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Conflicts of interest. The authors have no conflicts of interest to declare.

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References

1. **Li YC, Zhang JH, Yu GD.** A scenario-based hybrid robust and stochastic approach for joint planning of relief logistics and casualty distribution considering secondary disasters. *Transport Res E-Log.* 2020;141:102029.
2. **Akbari ME, Farshad AA, Asadi-Lari M.** The devastation of Bam: an overview of health issues 1 month after the earthquake. *Public Health.* 2004;118(6):403-408.
3. **Zhang Q, Sun XY, Tong F, *et al.*** A review of intelligent control algorithms applied to robot motion control. In: *2018 IEEE 8th Annual International Conference on CYBER Technology in Automation, Control, and Intelligent Systems (CYBER).* Tianjin: IEEE. 2018:105-109.
4. **Campbell S, Niall O'Mahony N, Carvalho A, *et al.*** Path planning techniques for mobile robots: a review. In: *2020 6th International Conference on Mechatronics and Robotics Engineering (ICMRE).* Barcelona: IEEE, 2020:12-16.
5. **Blackburn MR, Everett HR, Laird RT.** After action report to the joint program office: Center for the Robotic Assisted Search and Rescue (CRASAR) related efforts at the World Trade Center. 2002. Accessed May 7, 2021. https://www.hsdl.org/?view&did=713309
6. **Matsuno F, Sato N, Kon K, *et al.*** Utilization of robot systems in disaster sites of the Great Eastern Japan Earthquake. *Field and Service Robotics: Results of the 8th International Conference.* Berlin, Heidelberg: Springer. 2014;92:1-17.
7. **Rohmer E, Ohno K, Yoshida T, *et al.*** Integration of a sub-crawlers' autonomous control in Quince highly mobile rescue robot. In: *2010 IEEE/SICE International Symposium on System Integration.* Sendai: IEEE. 2010:78-83.
8. **Nagatani K, Kiribayashi S, Okada Y, *et al.*** Gamma-ray irradiation test of electric components of rescue mobile robot Quince. In: *2011 IEEE International Symposium on Safety, Security, and Rescue Robotics.* Kyoto: IEEE, 2011:56-60.
9. **Nagatani K, Kiribayashi S, Okada Y, *et al.*** Redesign of rescue mobile robot Quince. In: *2011 IEEE International Symposium on Safety, Security, and Rescue Robotics.* Kyoto: IEEE. 2011:13-18.
10. **Kruijff GJM, Pirri F, Gianni M, *et al.*** Rescue robots at earthquake-hit Mirandola, Italy: a field report. In: *2012 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR).* College Station, TX: IEEE. 2012:1-8.
11. **Kruijff-Korbayová I, Colas F, Gianni M, *et al.*** TRADR Project: long-term human-robot teaming for robot assisted disaster response. *Künstl Intell.* 2015;29(2):193-201.
12. **Kruijff-Korbayová I, Freda L, Gianni M, *et al.*** Deployment of ground and aerial robots in earthquake-struck Amatrice in Italy (brief report). In: *2016 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR).* Lausanne: IEEE. 2016:278-279.
13. **Wright C, Buchan A, Brown B, *et al.*** Design and architecture of the unified modular snake robot. In: *2012 IEEE International Conference on Robotics and Automation.* Saint Paul: IEEE. 2012:4347-4354.
14. **Rollinson D, Choset H.** Gait-based compliant control for snake robots. In: *2013 IEEE International Conference on Robotics and Automation.* Karlsruhe: IEEE. 2013:5138-5143.
15. **Rollinson D, Bilgen Y, Brown B, *et al.*** Design and architecture of a series elastic snake robot. In: *2014 IEEE/RSJ International Conference on Intelligent Robots and Systems.* Chicago: IEEE. 2014:4630-4636.
16. **Whitman J, Zevallos N, Travers M, *et al.*** Snake robot urban search after the 2017 Mexico City Earthquake. In: *2018 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR).* Philadelphia, PA: IEEE. 2018:1-6.
17. **Yamada S, Hirose S, Endo G, *et al.*** R-Crank: amphibious all terrain mobile robot. In: *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS).* Daejeon: IEEE. 2016:1067-1072.
18. **Klamt T, Behnke S.** Anytime hybrid driving-stepping locomotion planning. In: *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems.* Vancouver: IEEE. 2017:4444-4451.
19. **Kebritchi A, Havashinezhadian S, Rostami M.** Design and experimental development of hexapod robot with fiberglass-fibercarbon composite legs. In: *2018 6th RSI International Conference on Robotics and Mechatronics (IcRoM).* Tehran: IEEE. 2018:439-444.
20. **Sanfilippo F, Helgerud E, Stadheim PA.** Serpens, a low-cost snake robot with series elastic torque-controlled actuators and a screw-less assembly mechanism. In: *2019 5th International Conference on Control, Automation and Robotics (ICCAR).* Beijing: IEEE. 2019:133-139.
21. **Recchiuto CT, Sgorbissa A.** Post-disaster assessment with unmanned aerial vehicles: a survey on practical implementations and research approaches. *J Field Robot.* 2018;35(4):459-490.
22. **Delmerico J, Mintchev S, Giusti A, *et al.*** The current state and future outlook of rescue robotics. *J Field Robot.* 2019;36(7):1171-1191.
23. **Pretto EA, Barach P.** Principles and practice of disaster medicine: what every anesthesiologist should know about responding to medical disasters. *Adv Anesth.* 2008;26:175-199.
24. **Wuthisuthimethawee P, Lindquist SJ, Sandler N, *et al.*** Wound management in disaster settings. *World J Surg.* 2015;39(4):842-853.
25. **Blaivas M, Sargsyan AE, Karakitsos D.** Tactical emergency medicine, procedures, and point-of-care evaluation in austere environments. *Trauma Team Dynamics.* Cham: Springer. 2016:233-236.
26. **Ito K, Sugano S, Iwata H.** Wearable echography robot for trauma patient. In: *2010 IEEE/RSJ International Conference on Intelligent Robots and Systems.* Taipei: IEEE. 2010:4794-4799.
27. **Ito K, Tsuruta K, Sugano S, *et al.*** Evaluation of a wearable tele-echography robot system: FASTele in a vehicle using a mobile network. In: *2011 Annual*

International Conference of the IEEE Engineering in Medicine and Biology Society. Boston, MA: IEEE. 2011:2093-2096.
28. **Ito K, Sugano S, Iwata H.** Internal bleeding detection algorithm based on determination of organ boundary by low-brightness set analysis. In: *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*. Vila Moura: IEEE. 2012:4131-4136.
29. **Ito K, Sugano S, Iwata H.** Organ boundary determination algorithm for detecting internal bleeding. In: *2012 Annual International Conference of the IEEE Engineering in Medicine and Biology Society*. San Diego, CA: IEEE. 2012:3183-3186.
30. **Suthakorn J, Shah SSH, Jantarajit S, *et al.*** On the design and development of a rough terrain robot for rescue missions. In: *2008 IEEE International Conference on Robotics and Biomimetics*. Bangkok: IEEE. 2009:1830-1835.
31. **Treratanakulchai S, Suthakorn J.** Effective vital sign sensing algorithm and system for autonomous survivor detection in rough-terrain autonomous rescue robots. In: *2014 IEEE International Conference on Robotics and Biomimetics (ROBIO 2014)*. Bali: IEEE. 2014:831-836.
32. **Phuengsuk R, Suthakorn J.** A study on risk assessment for improving reliability of rescue robots. In: *2016 IEEE International Conference on Robotics and Biomimetics (ROBIO 2016)*. Qingdao: IEEE. 2016:667-672.
33. **Theobald D.** Mobile extraction-assist robot. US Patent 20080265821 A1. 2008.
34. **Wen J, Sun X, Shi Y, *et al.*** Patient influx and trauma types in a front-line hospital and a secondary referral hospital after the Wenchuan earthquake: a retrospectively comparative study. *Eur J Trauma Emerg Surg.* 2012;38(3):261-267.
35. **Bar-On E, Lebel E, Kreiss Y, *et al.*** Orthopaedic management in a mega mass casualty situation. The Israel Defence Forces Field Hospital in Haiti following the January 2010 earthquake. *Injury.* 2011;42(10): 1053-1059.
36. **Awais S, Saeed A.** Study of the severity of musculoskeletal injuries and triage during the 2005 Pakistan earthquake. *Int Orthop (SICOT).* 2013;37(8):1443-1447.
37. **Kang P, Tang BH, Liu Y, *et al.*** Profile and procedures for fractures among 1323 fracture patients from the 2010 Yushu earthquake, China. *Am J Emerg Med.* 2016;34(11):2132-2139.
38. **Bar-On E, Blumberg N, Joshi A, *et al.*** Orthopedic activity in field hospitals following earthquakes in Nepal and Haiti. *World J Surg.* 2016;40(9):2117-2122.
39. **Williams A, Sebastian B, Ben-Tzvi P.** Review and analysis of search, extraction, evacuation, and medical field treatment robots. *J Intell Robot Syst.* 2019;96(3):401-418.
40. **Sebastian B, Ben-Tzvi P.** Physics based path planning for autonomous tracked vehicle in challenging terrain. *J Intell Robot Syst.* 2019;95(2): 511-526.
41. **Sebastian B, Williams A, Ben-Tzvi P.** Control of a head stabilization system for use in robotic disaster response. In: *ASME 2017 International Mechanical Engineering Congress and Exposition*. Tampa, Florida. USA: ASME. 2017. 4A: Dynamics, Vibration, and Control.
42. **Sahashi T, Sahshi A, Uchiyama H, *et al.*** Study and development of the rescue robot to accommodate victims under earthquake disasters. In: *Informatics in Control, Automation and Robotics*. Berlin, Heidelberg: Springer. 2013:89-100.
43. **Gibney RTN, Sever MS, Vanholder RC.** Disaster nephrology: crush injury and beyond. *Kidney Int.* 2014;85(5):1049-1057.
44. **Sahashi T, Sahashi A, Uchiyama H, *et al.*** A study of operational liability of the medical rescue robot under disaster. In: *2011 IEEE/SICE International Symposium on System Integration (SII)*. Kyoto: IEEE. 2011:1281-1286.
45. **Zacharaki A, Kostavelis I, Gasteratos A, *et al.*** Safety bounds in human robot interaction: a survey. *Safety Sci.* 2020;127:104667.
46. **Sugiura R, Fujikawa T, Nishikata R, *et al.*** Soft tissue bruise injury by blunt impact in human-robot interaction - difference of tolerance between chest and extremities. In: *2019 19th International Conference on Control, Automation and Systems (ICCAS)*. Jeju, Korea (South): IEEE. 2019:792-797.
47. **Robinette P, Howard A, Wagner AR.** Conceptualizing people trust a robot that previously failed? *Autonomy and Artificial Intelligence: A Threat or Savior?* Cham: Springer. 2017:129-155.
48. **Nayyar M, Zoloty Z, McFarland C, *et al.*** Exploring the effect of explanations during robot-guided emergency evacuation. In: *International Conference on Social Robotics (ICSR)*. Cham: Springer. 2020:13-22.
49. **Rossi A, Dautenhahn K, Koay KL, *et al.*** How the timing and magnitude of robot errors influence peoples' trust of robots in an emergency scenario. In: *International Conference on Social Robotics (ICSR)*. Cham: Springer. 2017:42-52.
50. **Schneider FE, Wildermuth D.** Results of the European Land Robot Trial and their usability for benchmarking outdoor robot systems. In: *Conference Towards Autonomous Robotic Systems (TAROS)*. Berlin, Heidelberg: Springer. 2011:408-409.
51. **Sheh R, Schwertfeger S, Visser A.** 16 years of RoboCup rescue. *Künstl Intell.* 2016;30(3):267-277.
52. **Winfield AFT, Franco MP, Brueggemann B, *et al.*** euRathlon and ERL emergency: a multi-domain multi-robot grand challenge for search and rescue robots. In: *ROBOT 2017: Third Iberian Robotics Conference*. Cham: Springer. 2017:263-271.
53. **Brüggemann B, Wildermuth D, Schneider FE.** Search and retrieval of human casualties in outdoor environments with unmanned ground systems—system overview and lessons learned from ELROB 2014. *Field and Service Robotics*. Cham: Springer. 2016;113:533-546.
54. **Yanase J, Triantaphyllou E.** The seven key challenges for the future of computer-aided diagnosis in medicine. *Int J Med Inform.* 2019;129: 413-422.
55. **Yanase J, Triantaphyllou E.** A systematic survey of computer-aided diagnosis in medicine: past and present developments. *Expert Syst Appl.* 2019;138:112821.
56. **Kelton DK, Szulewski A, Howes D.** Real-time video telemedicine applications in the emergency department: a scoping review of literature. *Can J Emerg Med.* 2018;20(6):920-928.
57. **Zhang F, Yu H, Jiang J, *et al.*** Brain–computer control interface design for virtual household appliances based on steady-state visually evoked potential recognition. *Visual Inform.* 2020;4(1):1-7.
58. **Yadav D, Yadav S, Veer K.** A comprehensive assessment of Brain Computer Interfaces: Recent trends and challenges. *J Neurosci Methods.* 2020;346:108918.
59. **Aricò P, Borghini G, Di Flumeri G, *et al.*** Chapter 10 - a passive brain–computer interface application for the mental workload assessment on professional air traffic controllers during realistic air traffic control tasks. *Prog Brain Res.* 2016;228:295-328.
60. **Liu YZ, Habibnezhad M, Jebelli H.** Brain-computer interface for hands-free teleoperation of construction robots. *Automat Constr.* 2021;123: 103523.

https://doi.org/10.1017/dmp.2022.98 Published online by Cambridge University Press