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Review Article

Integrated the Medical Procedure Analyze Seismic Resilience of Healthcare System: A Critical Review from the Resilience of Healthcare System vs. Medical Demand Perspective

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The healthcare system is the bearer of treating the wounded and the victims of earthquakes. The functional integrity of the healthcare system is critical to the process of postearthquake medical rescue. Thus, the requirements for seismic resilience of the medical functions of the healthcare systems are increasing. Many studies have applied resilience research to address critical issues in the medical rescue of postearthquake casualties, such as medical diagnosis, emergency surgery, and intensive care. However, systematic construction is still lacking. System resilience is one of the most promising systemic management theories with great potential to address the abovementioned challenges. This article puts forward a scientific concept that system resilience can improve the efficiency of earthquake relief in medical rescue. Firstly, a scientific review of medical demand and medical resilience was conducted, summarizing resilience and resilience of healthcare system concepts. In addition, the postearthquake medical demand was reviewed, and the classification and distribution probability of postearthquake injuries were summarized. Furthermore, by reviewing the postearthquake medical rescue process, the weak points of each medical link were summarized. Combined with the key points in the medical rescue process, the application of resilience studies in the medical system is reviewed, and the progress of medical resilience is illustrated. In summary, combined with medical demand, the article provides some guidance for the deep integration between medical rescue processes and medical resilience and identifies the challenges of system resilience to reduce the waiting time of the injured future medical rescue in the earthquake.

1. Introduction

The casualty data in the historical earthquakes have proved the importance of the resilience of the healthcare system. According to the statistics of the international disaster database from EM-TAD [1], 1,489,333 people were injured in 467 earthquakes around the world from 2000 to 2021. There are more than 10,000 people who were injured in the earthquake. The degree of the wounded's injury varies. The patient's condition is complicated. It requires various specific medical procedures to achieve medical rescue. Meanwhile, the healthcare system accommodates damaged hospitals and still needs to maintain medical services continued after the earthquake. Therefore, higher requirements are put forward for medical rescue [2, 3].

The healthcare system is not only the undertaker of postearthquake medical rescue but also the victim of earthquakes. The historical earthquake data show that regional hospitals that have been damaged by the earthquake have declined the efficacy of medical rescue. For example, in the Mw7.6 Izmit earthquake, 10 hospitals suffered severe damage, which led to a large-scale emergency transfer of casualties [4]. In the Mw8.0 Wenchuan earthquake, because several hospitals were damaged, the medical rescue had to be carried out in temporary hospitals [5]. The Haiti earthquake caused total paralysis in local hospitals, which means that complex surgical operations could not be completed [6]. The healthcare systems suffered huge losses in the earthquake. Meanwhile, a large number of casualties were unable to receive timely and high-quality medical treatments which indirectly led to an increase in casualties and deaths [7]. Because the function of hospitals is interrupted, the casualties have to be transferred between the regional hospitals.

However, by improving the seismic resilience of the hospitals, the regional imbalance between medical demand and supply cannot be solved. An efficient operation mechanism of the regional healthcare system is also important to improve the efficiency of medical rescue. Thus, it is necessary to assess the functional seismic resilience of the regional healthcare system. The World Health Organization (WHO) and the Pan American Health Organization (PAHO) urged countries to develop policies to strengthen the capacity of healthcare systems to work collaboratively and improve the rational and efficient use of medical resources in regional healthcare systems [8, 9]. Based on the "Hyogo Framework for Action 2005–2015, Components of National and Community Disaster Resilience" [10], the 2015 world conference on disaster reduction proposed the "2015–2030 Sendai Disaster Risk Reduction Framework" [11]. It states that the country should undertake the main responsibility for disaster prevention and mitigation. The governments should improve medical disaster relief capabilities and support various organizations and departments to participate in coordinated medical operations. Due to the lack of data and transparency, the specific role of the first wave of medical rescue provided from countries all over the world to Haiti during the earthquake in 2010 could not be determined [12]. Postearthquake medical rescue forces include hospitals that retain functions after the earthquake, temporary emergency medical rescue, and medical evacuation. By utilizing medical resources rationally, the efficiency and quality of postearthquake medical rescue could be improved, and the number of postearthquake casualties could be reduced.

The resilience of the healthcare system is the key to guaranteeing the dynamic balance between the medical demands of the casualties and the medical capacity. Owing to the complex interdependence of society, infrastructure, and the natural environment, disaster processes and casualty outcomes are thus extremely difficult to predict. In the meantime, postearthquake medical rescue not only involves the study of the injuries and the process of medical rescue but also involves reducing the seismic loss of functions of the hospitals. This is undoubtedly a very challenging task, especially during earthquake relief. After many years of development, resilience theory has been applied to economics [13], engineering [14], sociology [15], environmental science [16], complex systems science [17], disaster prevention and mitigation [18], industrial engineering [19], business management [20], and other sciences and fields. Based on the practical effect of resilience theory in the above aspects, the application of resilience theory in the process of the medical rescue of a postearthquake healthcare system is also feasible.

This article proposes the concept of seismic resilience of the healthcare system combining medical demands and the process of medical rescue after the earthquake, which intends to improve the efficiency of postearthquake medical rescue and reduce the waiting time of the injured. Moreover, possible challenges in the postearthquake medical rescue process were highlighted.

This article is arranged as follows: Section 2 provides the review methodology. Section 3 reviews the concept of resilience, healthcare systems, and healthcare system resilience. Section 4 counts the medical demand of the injured after the earthquake in the literature. Section 5 reviews the medical rescue process and points out weak components in the process. Section 6 reviews the application of resilience in the medical rescue process. Section 7 gives the conclusions and outlook.

2. Method

2.1. Data Sources and Search Strategy. Retrospective studies on the medical demand of earthquake-related injuries and the medical rescue of the resilience of hospitals after earthquakes were published in English and Chinese, irrespective of publication status and article type. The investigators conducted a systematic literature search using the following electronic databases: PubMed (from 1990 to 2022), Web of Science (from 1990 to 2022), and Scopus (from 1990 to 2022). Two parts are medical demand ("earthquakes" and "wounds and injuries") and the medical capability of the hospital after earthquakes ("earthquakes" and "hospital" and "resilience" and "capacity" and "rescue"). We used the PubMed search, Web of Science search, and Scopus. Additionally, manual searches of references cited in all relevant original and review articles were conducted. If full texts were unavailable in the databases, we attempted to obtain information from the authors by e-mail.

2.2. Selection and Exclusion Criteria. For studies to be eligible for inclusion in the analysis, they had to fulfill the following criteria: For medical demand, (1) included a retrospective investigation of earthquake-related injury among inpatients after earthquakes; (2) provided a quantitative description of the types of direct physical injuries sustained in the aftermath of earthquakes; and (3) included earthquake-related injury patterns discussed in this study. The exclusion criteria were as follows: (1) described earthquake-related injury types, but did not include detailed percentages; (2) were not published in English; and (3) only reported psychological impact or indirect injuries from earthquakes. For resilience and the resilience of the healthcare system, (1) included the development of the concept of resilience; (2) the development of the concept of resilience in health systems; (3) quantitative analysis methods for resilience; and (4) the process of postearthquake medical rescue. The exclusion criteria were as follows: (1) ductile concepts and applications in materials science; (2) details of the medical rescue process (resource allocation and medical personnel efficiency); and (3) quantitative data statistics for medical system resilience analysis.

2.3. Search Results and Study Characteristics

2.3.1. For Medical Demand. Though 1548 records were retrieved by our search strategy, we excluded 1448 articles after reading the titles and abstracts and retained 237 articles for further evaluation by reading the full texts. Finally, we selected 47 full-text articles about earthquake-related injury patterns among inpatients after earthquakes, with sample sizes of patients ranging from 33 to 37387 and the earthquake magnitude ranging from 6 to 8.

2.3.2. For Resilience and the Resilience of the Healthcare System. Though 769 records were retrieved by our search strategy, we excluded 675 articles after reading the titles and abstracts and retained 245 articles for further evaluation by reading the full texts. Finally, we selected 101 full-text articles about resilience and the resilience of healthcare system, which include application of the concept of resilience in the healthcare system.

3. Concepts and Quantitative Analysis Methods

3.1. Concept of Resilience. Resilience is derived from the Latin word, that is, resilio, which means bounce to back [21]. The concept originated in physics to characterize the resistance of materials to impact. In the 1970s, ecologist Holling [22] first used the concept of resilience to describe the multiequilibrium state of ecosystems, which is the character of the ability of ecosystems to absorb changes in response to disturbances. Resilience has been more widely used in psychology, engineering, ecology, etc. At present, there is no accepted definition of resilience in academia (Table 1). Moreover, its meaning varies within the same field of research.

Resilience can be divided into two concepts: engineering resilience and ecological resilience. Engineering resilience is a one equilibrium state in the system. Its resilience is manifested in the fact that the system can resist disturbances and maintain its original state. System resilience can be measured by the resistance of the system to disturbances and the rate at which it returns to the original equilibrium state. Ecological resilience advocates the existence of multiple equilibrium states in the system. The resilience of the system is measured by the level of disturbances that the system needs to absorb from one equilibrium state to another. Based on previous research, Folke [37] analyzed the interaction between humans and ecosystems and further proposed socio-ecological resilience. This view holds that the system is constantly changing and maintained in a certain equilibrium that formal perturbations cause a continuous change in the system. Resilience describes not only the ability of a system to absorb disturbances to maintain its original state but also the ability of the system to self-organize and learn and adapt. Resilience which does not emphasize equilibrium is also known as evolutionary resilience.

The inconsistency of the above concepts of resilience poses challenges to studying the resilience of urban systems and subsystems. How to define the resilience of urban systems and subsystems depends on the understanding of this issue. Problems were researched in two ways. One is induction, which is from individual to general. The second is the deduction, which is from general to individual. Holling [22] proposed the concept of resilience based on the observation of the development of their biological populations, which belongs to the inductive process. From the initial concept of resilience to socio-ecological resilience and resilience of urban systems and subsystems, the process of development of this concept is more analogous to the deduction. Different from the objective resilience of ecosystems, the resilience connotation of the urban system in which humans live has both subjective and objective aspects. Resilience is an objective attribute of urban systems and subsystems. Historical cases show that cities have certain resilience after encountering disturbances such as disasters. What level of resilience do cities hope to achieve? How to reach it depends on human subjective consciousness. In general, the resilience of urban systems and subsystems refers to the ability to maintain or quickly restore the core functions in the event of various disturbances such as disasters, and to adapt to future uncertainties.

The performance of resilience has an obvious process. There are two main links: resistance and recovery. Resistance means that the system can withstand the negative effects of perturbations to maintain its core function. Recovery means that a system can quickly restore its functionality to the desired state after being compromised. This state may be the initial state, in which the system is considered to have a single equilibrium state. It can also be a new state, in which the system has a multiequilibrium state. In addition, adaptation is also an important connotation of resilience, which means that the system can change its structure through self-learning to prepare for future uncertain disturbances. The system adapts to improve its resistance and resilience to future disturbances. The system is constantly resisting, recovering, and adapting, leaving it in a dynamic process of constant evolution.

For studying resilience, it is necessary to clarify resilience of what, to what, for what, for whom, and over what time frame. Firstly, studying resilience begins with defining systems and their boundaries. The different systems have different qualities that directly affect the understanding of resilience. Secondly, it is necessary to define the type of system disturbance, and improving the resilience of the system to one disturbance may reduce its resilience to other disturbances. It is also necessary to clarify the service targets or stakeholders of system resilience, and different stakeholders will have different requirements for the goal of resilience. Finally, the time window for observing the resilience of the system should be clarified, because the choice of time scale will affect the choice of disturbance type and the evaluation of the recovery.

3.2. Concept of Healthcare System Resilience. The World Health Organization [38] defines the health system as an organization that covers all activities aimed at promoting, restoring, and ensuring the health, including relevant public, private, and nongovernmental institutions such as hospitals,

Table 1: Different definitions of resilience.

Authors	Date of publication	Definition of resilience
Holling [22]	1973	Resilience refers to the ability of a system to absorb, change, and perturb and to maintain a balanced state of the system
Wildavsky [23]	1988	Resilience refers to the ability to cope with disasters after a disaster and has the characteristics of adaptation and recovery
Mileti [24]	1999	Resilience refers to the ability of an area to undergo extreme natural events without catastrophic loss, damage, reduced productivity, and normal life and does not require a lot of outside assistance
Comfort [25]	1999	Resilience refers to the ability and action of existing resources and capacities to adapt to new situations
Adger [26]	2000	Resilience refers to the resilience of public infrastructure to disaster shocks
Klein et al. [16]	2003	Resilience is the ability to withstand the stresses of the environment
Bruneau et al. [27]	2003	Resilience refers to the ability of a society to mitigate the impact on the city and to cope with the impact of future disasters with the least impact on society
Walker et al. [28]	2004	Resilience consists of four components: range, resistance, instability, and chaos. Toughness refers to the ability of a system to absorb interference and keep its key functions, structures, and characteristics functional
Walker and Slat [29]	2006	Resilience was originally defined as the ability of a system to respond to external disturbances in the case of maintaining its basic state
Allenby and Fink [30]	2005	Resilience refers to the ability of a system to maintain its functional and structural stability in the face of internal and external changes, and only when the function and structure are slowly declining
US Department of Homeland Security [31]	2006	Resilience refers to the ability of the system to efficiently reduce the degree of damage to the system by disasters at a set target functional level in the event of an emergency
Wamsler [32]	2007	Resilience refers to the ability of urban systems to survive, adapt, and develop in the face of sudden disasters
UNISDR [33]	2009	Resilience refers to the exposure of a system, community, or society to a hazard, the ability to resist, absorb, adapt to disasters, and effectively reduce below the target
United Nations [34]	2009	Resilience is defined as the ability of systems, communities, or societies exposed to hazards, to resist, absorb, withstand, and recover from the impacts of disasters in a timely and effective manner, including the protection and restoration of essential infrastructure works and their functions
Cohen et al. [35]	2013	Resilience is defined as the ability of a society to function properly in times of crisis
Resilience Alliance [36]	2022	Resilience is the ability of socio-ecological systems to absorb disturbances and pressures from maintaining the original characteristics, especially their original structure and function

health centers, testing centers, pharmacies, and blood banks. The U.S. Department of Health and Human Services [39] defines the healthcare system as a collection of all medical organizations in the community. Chinese healthcare system [40] includes not only a collection of various medical organizations and institutions, but also a complex of many interacting and interdependent elements committed to the various resources of the health system to achieve the purpose of disease prevention and treatment and improve the health level of the population.

The concept of the resilience of the healthcare system has not yet been unified (Table 2). However, the studies all emphasize the resilience of the healthcare system to maintain services under shocks, or absorb the adverse effects of shocks through its adaptation and change in the process of resistance, to ensure the continuity of medical services, or restore the function as soon as possible after the function of the healthcare system has received a significant loss to ensure subsequent services. Therefore, the resilience of health systems remains a discussion of the ability of health systems to resist shocks, maintain their healthcare functions, and quickly recover from health services after being affected.

3.3. Quantitative Assessment Methods for the Resilience of the Healthcare System. It is necessary to evaluate the resilience of the system under specific conditions, to the improvement of the resilience of existing systems or the design of new systems. The accuracy of the resilience evaluated greatly affects the effectiveness of the work. Resilience assessments can be both qualitative and quantitative, depending on the characteristics of the object being assessed and the analytical needs. The qualitative methods for assessing resilience mainly include questionnaires and focus group discussions [54], which are simple in principle and highly operable. However, the results are often limited by personal knowledge. The quantitative methods for assessing resilience mainly include two categories: functional curve and scorecard model (Table 3), which can obtain more objective results of the resilience. However, the calculation process is more complicated.

Bruneau et al. [27] argue that resilience can be quantified by four dimensions. These four dimensions include technical, organizational, social, and economic (TOSE) (Figure 1). Different dimensions require different quantification methods. There may be different quantification methods for different engineering systems even for the same dimension. Therefore, there are several ways to quantify the resilience of healthcare systems (Table 3). Meanwhile, there are four characteristics of resilience, which are robustness, redundancy, resourcefulness, and rapidity (4R) (Figure 1). These four characteristics are coupled with each other, indicating the inconsistency of the toughness quantification method.

Rational assessment resilience indices are the key to quantitative healthcare system. One way to do so is through defining the service as a function of losses to different hospital departments while considering the possibility of service redistribution among the departments. Denver Health [67] based on hospital capacity or the number of staffed beds available for patients based on daily rates, defined the quantity portion of the offered medical services. Jacques et al. [48] examined the loss and redistribution of n critical clinical and support services at a hospital. Hassan and Mahmoud [68] modified the fault tree proposed by Jacques et al. [48] and regarded the available beds as the quantitative functionality. Estimating patients demand is a critical parameter for hospital functionality assessment. Zhai et al. [69] adopted the ratio of the number of patients treated to the total number of patients to measure the hospital functionality. In addition to medical service, treatment provided timely can reduce the risk of disability and death. Different time limits are given to patients, and medical resources need to be available to begin treatment as soon as possible. The time limit is known as the critical waiting time (WT), and the waiting time is defined as the time a patient is waiting before receiving assistance from medical workers, which does not include the time before entering hospitals [70]. The waiting time of patients and the number of patients treated within the critical waiting time are important index for quantitative analysis of hospital functions. The relevant indices for the quantification of hospital functions are shown in Table 3.

Methods of quantitative resilience assessment are used in most of the relevant research in the field of evaluating resilience. Therefore, the scorecard model and functional curve are widely applicated. The scorecard model can be applied to different objects and multiple types of hazards. It consists of a series of indicators lists describing the resilience state and the corresponding scoring scales of the system. The indicators listed are scored sequentially according to the actual situation after the disasters. According to weighted aggregation or multiple regression of the score of each of the indicators, the score of system resilience is calculated.

The functional curve quantifies resilience by analyzing the data produced in the process of recovery. Based on the random factors of the system that are directly reflected in the measure expression, the functional curve is divided into deterministic measures and random measures. The functional curve is the geometric characteristic of the recovery curve to resilience.

The equation of the functional curve proposed by Bruneau et al. [27] is representative (equation (1)). This equation is proposed to achieve community seismic resilience. However, the most critical functional variable in its expression represents a broad concept. Therefore, it has good applicability and can be used to measure the resilience of different types of objects and disasters.

$$R = \int_{t_0}^{t_0+t_{LC}} \frac{Q(t)}{t_{LC}} \mathrm{d}t, \quad (1)$$

where t is the time variable, R is community seismic resilience, $Q(t)$ is community functionality standardized at moment t, and t_0 and t_{LC} represent the time when the earthquake occurred and the time when the community recovered, respectively.

Table 2: Definition of healthcare system resilience.

Authors	Date of publication	Definition of medical resilience
Kieny and Dovlo [41]	2015	The resilient healthcare system absorbs the impact of emergencies while continuing to provide routine care
Barasa et al. [42]	2017	Resilient healthcare systems need to be able to adapt and change to continue to deliver quality services and respond to emerging healthcare needs
Kruk et al. [43]	2015	The health system is defined as the ability of healthcare practitioners, institutions, and populations to prepare for and respond effectively to crises. A resilient healthcare system is perceptual and can preidentify potential risk factors affecting people's health
Blanchet et al. [44]	2017	The willfulness of a health system is defined as the ability of a health system to absorb, adapt, change, and maintain control over its original structure and function when exposed to shocks, such as infectious diseases, geological disasters, and armed conflicts
Zhong et al. [45]	2014	Hospital disaster resilience is defined as the ability of a hospital to resist, absorb, and respond to disaster shocks, maintain its essential functions (such as prehospital emergency care, hospital emergency, intensive care, disinfection, and isolation), and return to its original state or a new adaptive state
Cimellaro and Pique [46]	2016	Hospital disaster resilience is defined as the ability of a hospital system to prepare for a disaster event, absorb the effects of the disaster, recover from the disaster, and keep itself functioning well
World Health Organization [47]	2015	A resilient health system is defined as a health system that can predict, respond to, recover, and adapt to climate-related shocks or stress diseases in unstable climates to ensure the health of populations with increasing health, and considers that resilience of health systems equals reduced vulnerability plus increased adaptive capacity
Jacques et al. [48]	2014	Disaster resilience of health systems refers to a hospital's ability to manage and continue to deliver healthcare in the event of an emergency, including the climate recovery phase
Ramandi and Kashani [49]	2018	Disaster resilience in health systems is the ability of hospitals to respond, withstand, and absorb the effects of disasters, provide health care services, and restore basic or acceptable levels of services
Berg and Aase [50]	2019	Resilience is described as a set of cognitive and behavioral strategies of individuals who enact resilience within an organizational context
Wiig et al. [51]	2020	A resilient healthcare system might be expected to consistently deliver high quality care, withstand disruptive events, and continually adapt, learn, and improve. The capacity to adapt to challenges and changes at different system levels, to maintain high quality care
Lyng et al. [52]	2021	This study develops a new conceptual account of adaptation and innovation as a basis for resilience in healthcare. Findings emerging from this study indicate that a balance between adaptation and innovation should be sought when seeking resilience in healthcare
Pei et al. [53]	2022	This article proposes a resilience assessment framework for the interdependent transportation–healthcare system integrating physical loss and organizational management during postearthquake emergency response. Considering the earthquake-induced injured people, the seismic damage to transportation, and the quantification of the condition of the patients after being treated, a novel metric is proposed to evaluate the response effort during the first 72 h

According to the above studies, the scorecard model is not quantitative enough, which is difficult to evaluate the improvement measures of resilience. Meanwhile, it is difficult to dynamically observe the functional performance of the resilience process of the healthcare system. The functional curves can make up for the shortcomings of the scorecard model. However, the functional curves are mostly used for single hospitals and lack the functional indicators of the hospital system and the comprehensive resilience that takes into account the postearthquake functional damage and recovery process.

4. Medical Demand after an Earthquake

A surge in medical demand that extends beyond local medical surge capacity in mass casualty incidents following major disasters is common. Shen et al. [71] elaborate the precision strategy of augmenting medical surge capacity for disaster response. Kato et al. [72] predicted under a maximal damage scenario in a future earthquake, we predicted a shortage of 2,780 beds for the treatment of severe casualties across Tokyo. Therefore, the study of the medical demand of earthquake casualties has become the key to providing medical relief for casualties in future earthquakes.

Table 3: The quantitative approach to healthcare system resilience.

Method	Quantification of resilience in healthcare systems	Feature equations	Literature sources
Scorecard model	In terms of hospital geographic information, structural safety, nonstructural safety, and medical functional safety, 145 evaluation indicators were established	N.A	[55]
	There are 43 evaluation indicators in eight areas: hospital safety, emergency leadership and cooperation, emergency preparedness, disaster material management, emergency personnel, emergency training and drills, critical emergency response capacity, and recovery and adaptation mechanisms	N.A	[56]
	151 indicators were used to evaluate the performance of four modules, including potential hospital risk, structural safety, nonstructural safety, and disaster emergency management, to quantify the disaster resilience of the healthcare system	N.A	[47]
	The hospital function was quantified by the scoring weighted summation results of 38 different component indicators, among which 38 indicators had different weight coefficients	N.A	[57]

Table 3: Continued.

Method	Quantification of resilience in healthcare systems	Feature equations	Literature sources
Functional measures	Hospital functions are divided into four subfunctions: structured, nonstructured, lifeline, and personnel. Then, the respective functions of different functional levels are fully arranged and combined to form a functional tree. Hospital functions are further quantified according to each combination, to quantify hospital functional resilience	—	[58]
	Define hospital functions based on fault trees, and gradually split hospital functions into multiple functional groups. Hospital resilience was finally determined by judging the functional level of the underlying group and going through a series of conduction paths	$Q(t) = \sum_n w_i (1 - (1 - R_i(t))L_i(t)/\sum_n w_i$	[48]
	The integral of the healthcare system function curve quantifies the disaster resilience of the healthcare system. The ratio of the number of healthy people in the disaster event to the healthy population reviewed before the disaster event was used as a quantitative indicator of the postdisaster hospital function of the health care system	$Q(t) = \begin{cases} \max((N_{WT_{crit}} - N_{WT_0}) - N_{WT,0})/N_{WT_{crit}} - N_{WT_0} \\ N_{WT} \le N_{WT_{crit}} \\ N_{WT_{crit}} - N_{WT_0}/\max(N_{WT_{crit}}, N_{WT} - (N_{WT_{crit}} - N_{WT_0})) \\ N_{WT} > N_{WT_{crit}} \end{cases}$	[59]
	The disaster resilience of the healthcare system is divided into three types of resilience indicators (${RI_h}^{Ph,M}$) for different services: traffic resilience indicators (${RI_F}^{Ph,M}$), ambulance resilience indicators (${RI_A}^{Ph,M}$), and hospital resilience indicators (${RI_H}^{Ph,M}$)	$RI_M^{ph} = \sum_h w_h^{ph,M} \cdot RI_h^{ph,M} / \sum_h w_i^{ph,M}$	[60]
	The integral of the healthcare system function curve quantifies the disaster resilience of the healthcare system. The function of individual hospitals is quantified in time by treating the wounded	$Q(t) = \begin{cases} \max((WT_{crit} - WT_0) - WT, 0)/WT_{crit} - WT_0 \\ WT \le WT_{crit} \\ WT_{crit} - WT_0/\max(WT_{crit}, WT - (WT_{crit} - WT_0)) \\ WT > WT_{crit} \end{cases}$	[61]
	Based on the proportion of injured patients, a segmented functional index was proposed, and this was used as a functional index to calculate hospital disaster resilience	$Q(t) = \begin{cases} A/P(t) A \le P(t) \\ 1 A \ge P(t) \end{cases}$	[62]
	A quantitative methodology that computes the capacity of hospitals to operate on injured people in the aftermath of a seismic event is presented. The model incorporates variables such as organizational and human preparedness, damage to buildings, the number of operating theatres, the amount of supplies, and the duration of a surgical treatment	$\mathrm{HOC}_{\mathrm{TOT}} = \sum_{i=1}^{n} \alpha_i \cdot \beta_i \cdot \gamma_i \delta_i / t_i \cdot k_i$	[63]
	The objective function $C_1(X)$ measures waiting time across the city as the average time that a patient would take since the earthquake until completing treatment in the operating room	$C_1(X) = \sum_{t \in T} \sum_{j=i+n_h}^{i \in \Gamma} \{t + \tau_{i,j}\} \times x_{i,j}(t) \times dt / \sum_{t \in T} \sum_{i \in \Gamma} b_i(t)$	[64]
	The probability of total functionality of the healthcare system, $P(Q)$, can be expressed as a combination of the probability of quantity, $P(Q_V)$, and the conditional probability of quality, $P(Q_S \mid Q_V)$, of the offered service	$P(Q(t)) = P(Q_V(t)^{\alpha V}) \cdot P(Q_S(t)^{\alpha S} \mid Q_V(t)^{\alpha V})$	[65]
	Hospital operating capacity (HOC) should be defined as the minimum of all the availability probabilities of the departments on the hospital treatment chains for a certain type of patients, which should be a number not more than 1 (can also be set as percentage)	$\mathrm{HOC}_{\mathrm{total}} = \sum_{s=1}^{n} w_s \cdot \mathrm{HOC}_s$	[66]

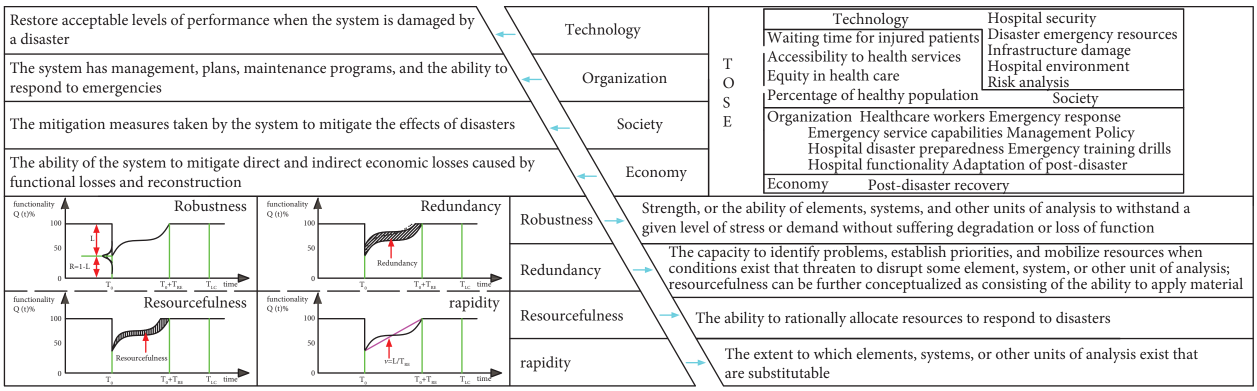

Figure 1: Resilience analysis of four dimensions (TOSE) and four characteristics (4R).

4.1. The Statistics of the Medical Demand. We calculated the incidence of earthquake-related injuries based on the percent published in each study. To explore the source of heterogeneity, we divided the studies by the magnitude of the earthquake. Combined with the classification and statistics of method of casualties put forward by Tang et al. [73], this article expands the casualty statistics from three aspects: injury types, injury parts, and injury factors. Casualty injuries are divided into fracture (F), soft tissue injury (ST), infection (I), nerve injury (NI), burn (B), crush (C), and amputation (A). Injury parts are divided into multiple injuries (M), internal organs (I), head/face/neck (H), trunk (TK), extremities (E), thorax (T), abdomen (AB), and spine (S). Injury factors are divided into crush/burying (C/B), slip/falling (S/F), and hit by an object (H). This article counts the number of casualties in earthquakes of magnitude 6 or higher from 1988 to 2016 (Table 4). Figure 2 shows the proportion of different casualty types.

According to the statistics of injury types of the wounded, it can be found that the number of fractured injuries accounts for the largest proportion, which is 44.83%. More than half of the wounded were fractures and soft tissue injuries. Although the proportion of wounded with crush injuries is few, the number of literatures on this type of wounded is relatively large, which is 30.

The largest number of injured are extremities injuries, accounting for 47.15%. The number of trunk injuries accounted for 27.34%. Earthquake casualties also often had multiple injuries, accounting for 13.06%. The percentage of wounded in the chest, abdomen, and vertebral column is 8.76%, 5.63%, and 8.52%, respectively. The main cause of injury in the earthquake was being hit by an object, accounting for 50.81%. Crushing/falling and slipping are the other two factors that cause injuries, 25.20% and 28.35%, respectively.

4.2. The Analysis of the Medical Demand. The conditions of the injured after the earthquake are different. The treatment process required is far different. It is necessary to combine the hospital reception data to study the classification and proportion of the condition of the injured after the earthquake. The postearthquake casualties are mainly fracture injuries, in which multiple injuries, head injuries, and spinal cord injuries have a high fatality rate, and the probability of sequelae is relatively large.

This reflects the fact that orthopedic surgery has been the means of inpatient medical relief for rescue since the earthquake. Therefore, it is crucial to prepare adequate medical equipment and personnel for medical rescue in future disasters. According to statistics of the injured at the Tribhuvan University Hospital in the 2015 Nepal earthquake, the peak of postearthquake casualty admissions occurred on the fifth day after the earthquake, and 89% of the casualties developed physical injuries, including 66% of bone injuries and received surgical treatment [118]. Postearthquake rescue data statistics showed that the change in the condition of the injured mainly presented as orthopedic and trauma-based in the early stage, and the number of medical patients gradually increased with the change of extrusion time [119, 120]. In the statistical analysis of the disease types of international rescue teams in Pakistan and Indonesia, trauma/wound diseases were predominant in the week after the earthquake, accounting for 61.46% to 79.52% and 61.48% to 72.35% in Pakistan and Indonesia, respectively. After one-week, other medical diseases increased significantly, accounting for 33.93% to 71.11% and 31.50% to 52.11% in Pakistan and Indonesia, respectively [112].

The most frequently traumatized part of the body is the extremities. This may be due in part to the fact that patients with injuries to the extremities survive longer than those with chest, abdominal, or head trauma [97]. Currently, the statistics of postearthquake injury are derived from the number of injured patients accepted by medical facilities for investigation. This has resulted in some spinal, thoracic, and cranial injuries not surviving due to the severity of the injuries, resulting in these injuries not being counted, although spinal, thoracic, and cranial injuries are rare, which are often serious and life-threatening, and cannot be ignored.

The statistics of crush injury casualties found that most of them were injured in multistory building structures such as brick-concrete structures, frame structures, or frame-shear structures [121]. By studying the number of crush injuries in the rural areas in Wenchuan, Lushan, and Yushu earthquakes, the proportion of crush injuries was relatively small compared to the urban areas. This is because most of

Table 4: The general characteristic of the 47 studies.

	Authors	Date of publication	Earthquake name	Sample	Magnitude
1	Armenian et al. [74]	1997	1988 Armenian earthquake	1454	6.9
2	Bai and Liu [75]	2009	2005 Pakistan earthquake	426	7.8
3	Dhar et al. [76]	2007	2005 Pakistan earthquake	468	7.6
4	Milch et al. [77]	2010	2007 Peru earthquake	92	8
5	Emami et al. [78]	2005	2003 Iran earthquake	708	6.5
6	Farfel et al. [79]	2011	2010 Haiti earthquake	318	7.0
7	Hatamizadeh et al. [80]	2006	2003 Iran earthquake	2086	6.8
8	İskit et al. [81]	2001	1999 Turkey Marmara earthquake	33	7.4
9	Jain et al. [82]	2003	2001 India earthquake	62	7.9
10	Jian et al. [83]	2010	2008 Wenchuan earthquake	196	8.0
11	Kuwagata et al. [84]	1997	1995 Japan earthquake	2702	7.2
12	Mohebbi et al. [85]	2008	2003 Iran earthquake	1332	6.6
13	Mulvey et al. [86]	2008	2005 Pakistan earthquake	1502	7.8
14	Parasuraman [87]	1995	1993 Iran earthquake	4803	6.4
15	Peek-Asa et al. [88]	2003	1994 California earthquake	171	6.7
16	Poçan et al. [89]	2002	1999 Turkey earthquake	630	7.4
17	Pointer et al. [90]	1992	1989 California earthquake	1082	7.1
18	Roces et al. [91]	1992	1990 Philippines earthquake	363	7.7
19	Roy et al. [92]	2002	2001 India earthquake	283	6.9
20	Sabzehchian et al. [93]	2006	2003 Iran earthquake	119	6.5
21	Salinas et al. [94]	1998	1994 California earthquake	329	6.7
22	Shoaf et al. [95]	1998	1994 Northridge earthquake	149	6.7
23	Tanaka et al. [96]	1999	1995 Japan earthquake	2718	7.2
24	Uzun et al. [97]	2005	1999 Turkey earthquake	75	7.4
25	Yang et al. [98]	2009	2008 Wenchuan earthquake	533	8.0
26	Zhang et al. [99]	2009	2008 Wenchuan earthquake	1723	8.0
27	Zhao et al. [100]	2011	2008 Wenchuan earthquake	192	8.0
28	Kang et al. [101]	2012	2010 Yushu earthquake	2622	7.1
29	Ding et al. [102]	2015	2008 Wenchuan earthquake	465	8.0
30			2015 Nepal earthquake	71	8.1
31	Wen et al. [103]	2012	2008 Wenchuan earthquake	2881	8.0
32	Zhang et al. [104]	2014	2013 Lushan earthquake	2010	7.0
33	Kang et al. [105]	2015	2013 Lushan earthquake	266	7.0
34	Hu et al. [106]	2012	2008 Sichuan earthquake	101	8.0
35	Li et al. [107]	2012	2010 Yushu earthquake	582	7.1
36	Doocy et al. [108]	2013	2010 Haiti earthquake	6696	7.0
37	Qiu et al. [109]	2010	2008 Sichuan earthquake	3401	8.0
38	Gu et al. [110]	2010	2008 Sichuan earthquake	92	8.0
39	Fan et al. [111]	2011	2008 Sichuan earthquake	1038	8.0
40	Lin et al. [112]	2016	2016 Taiwan earthquake	513	6.4
41	Li et al. [113]	2009	2008 Sichuan earthquake	32	8.0
42	Lin et al. [114]	2009	2008 Sichuan earthquake	28008	8.0
43	Johnston et al. [115]	2014	2010/2011 Canterbury earthquakes	9427	6.3–7.1
44	Xu et al. [116]	2013	2008 Sichuan earthquake	37387	8.0
45	Liu et al. [117]	2014	2008 Sichuan earthquake	334	8.0

the buildings in rural areas are adobe structures or brick-wood structures, which have only one floor [122]. Although buildings in rural areas have poor seismic performance and are severely damaged in earthquakes. But the rescue of the injured in this part is easier compared to multistory buildings.

People are most likely to be injured by falling objects during an earthquake. During an earthquake, try to avoid taking shelter under objects that easily fall. Therefore, the spread of proper earthquake self-rescue methods is very important to reduce the number of injuries. Keep your head, abdomen, and chest protected under a solid table or bed to avoid fatal injuries during an earthquake. Meanwhile, stay away from fire sources to avoid burns. Leave the building as soon as possible after the main quake to avoid injuries caused by aftershocks.

In summary, the medical rescue force with adequate health resources and equipment, especially for the extremities, is critical in the first hours after the earthquake. In addition, a detailed earthquake medical management plan should also adhere to a flexible approach to replenishing medical resources based on the distribution of different injury locations under different earthquake magnitudes.

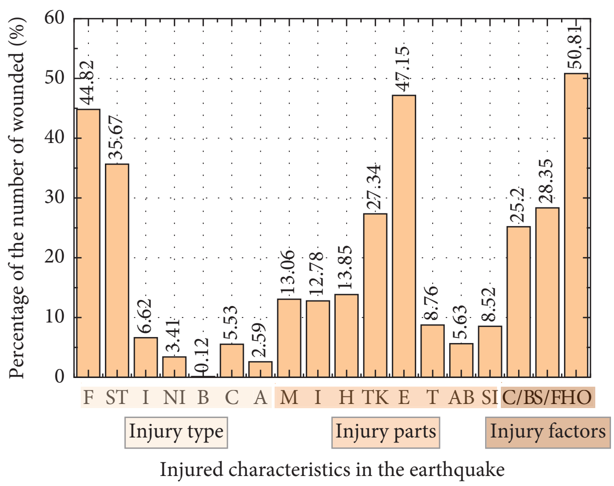

Figure 2: Injured characteristics in the earthquake.

5. The Function Capability of the Hospital

When a disaster occurs, hospitals are required to increase their receiving and treatment capacity in a very short time to meet the surge of patients. This aspect is referred to as surge response capability [123] and is conceptually defined as the combination of surge capacity and planning [124]. Medical capacity is "the ability to respond to a sudden increase in patient care demands" [125]. Achour et al. [126] optimized a reactive approach to natural hazards, which included physical and human, and increasing the resilience and flexibility of infrastructure to expand medical capacity. Therrien et al. [127] related insights from resilience research to the four "S" of surge capacity (staff, stuff, structures, and systems) and proposed a framework based on complexity theory to better understand and assess resilience factors that enable the development of surge capacity in complex health systems. A large number of medical resources and a rational medical rescue process become crucial to meet the medical demand.

5.1. Medical Rescue of the Wounded after the Earthquake. Based on the functional curve, the postearthquake function of the healthcare system should be clarified for evaluating the seismic resilience of the healthcare system. The literature shows that there is no uniform concept of the function of the healthcare system. The expectation of the healthcare system should be to protect human health. For this purpose, the healthcare system needs to provide a variety of medical services, including but not limited to physical examination, patient isolation, disease treatment, patient care, and disease prevention [39, 128]. It is essential to meet the medical demand of the injured in the earthquake for the medical function of the healthcare system in the disaster region.

The earthquake instantly caused a large number of casualties, which easily caused a shortage of doctors and medical resources. Therefore, the medical rescue of casualties adopts a graded rescue method [129]. The medical rescue system after the earthquake learned from the treatment precept used in the war. The medical rescue process is divided into three levels, which include on-site rescue, early treatment, and specialized treatment. The first level of treatment is an on-site rescue, which mainly includes self-rescue and mutual rescue of the injured at the scene of the disaster, as well as on-sitefirst-aid activities. Diagnosis and treatment activities include hemostasis, dressing, classification of injuries, anti-infection, and some simple surgeries. After the on-site rescue, the injured were transferred to hospitals and other medical institutions for follow-up medical treatment. The second level is early treatment. Early treatment is when a patient is sent to the hospital for treatment. Hospitals in disaster-stricken areas have been damaged by earthquakes. However, those hospitals still retain certain medical rescue functions, and can still carry out early treatment of patients and surgical treatment as appropriate. However, some of the wounded with complex conditions do not recover after receiving early treatment. At this time, the casualty needs to receive the third level of medical treatment (i.e., specialized treatment). Specialist care should be performed in well-functioning medical conditions.

According to the treatment site, postearthquake medical rescue can be divided into prehospital treatment and in-hospital treatment. Level 1 medical assistance is a part of the prehospital treatment. Second and tertiary-level medical assistance is considered in-hospital treatment. The key to prehospital treatment in the disaster area is to improve the survival rate of the injured after the earthquake. In-hospital treatment is to reduce the disability rate and radically treat the wounded. Therefore, it is necessary to consider the medical rescue function in the entire medical rescue process, when modeling or analyzing the postearthquake functional resilience of systems. The literature shows that the functional curves and scorecards model focuses on the comprehensive consideration of in-hospital medical function loss or recovery medical rescue process.

5.2. Medical Rescue Procedure in the Hospital during the Earthquake. Combined with the medical process in the evaluation of seismic resilience of healthcare systems, it helps decision-makers to formulate effective response strategies at all stages of earthquake disaster medical rescue. The key groups or weak links that have the greatest impact on the seismic performance of the system can be identified by the evaluation of seismic resilience. All aspects of medical rescues, such as injury diagnosis, surgical first aid, hospitalization, and ICU observation, should be considered when evaluating the seismic resilience of the healthcare system.

The classification of the injured has become the key to the postearthquake medical rescue when facing a large number of wounded. The medical device plays an important role in medical diagnostics. The 2016 Kumamoto earthquake, which caused the interruption of medical imaging equipment in 5 out of 9 hospitals, overloaded the medical imaging diagnosis work of the other 4 hospitals, resulting in waiting times longer than normal time of the injured. Medical device auxiliary diagnosis of diseases improves the quality of medical diagnosis, and the diagnostic efficiency of medical devices is a key factor restricting the function of the hospital system (Table 5).

After the diagnosis of the casualty, some of the wounded needed to be admitted to the emergency department for surgery. The emergency department must provide crucial medical care. Providing uninterrupted medical care in the emergency department is essential for medical rescue after the earthquake. According to the Chi-chi earthquake of 1999, 566 patients were admitted to the hospital within 3 days. In particular, the emergency department accepted 301 patients 10 hours after the earthquake [119]. Nieh et al. [138] found that emergency departments received 89.4% of casualties in the 2018 Hualien earthquake. The serious injury rate was 8.2%, indicating that moderate casualties were the majority injured in the emergency department. Emergency departments were under great pressure to treat those wounded.

To alleviate the pressure of medical rescue in the emergency department, the relationship between the workload of the emergency department and the medical demands was studied. Chu and Zhong [139] studied the correlation between the dynamics of emergency workload and medical demand. According to the statistics of casualties arriving at the emergency department after the earthquake, the number of casualties in the first three days after the earthquake was 3-5 times that of the predisaster period. After 4-5 days, the number of patients gradually returns to preearthquake levels [94]. Similarly, during the 2011 East Japan Earthquake, the number of patients admitted to the emergency department increased by 23% after the earthquake based on the utilization rate of emergency department resources at the University of Tokyo tertiary hospital [140]. Lin et al. [141] compared the rapid triage approaches to the emergency department. The results showed that both rapid triage methods in the emergency department could improve the quality and speed of emergency department treatment. For the degree of dependence on medical equipment, the casualty triage strategy can greatly reduce the waiting time for the casualty in the emergency.

Facing a large number of casualties after an earthquake, timely treatment and close monitoring are critical in saving lives. Huang et al. [142] discussed the treatment process of 18 patients in ICU during the Lushan earthquake and found that a reasonable ICU workflow can minimize the fatality rate of the injured. Treatment of injuries such as respiratory stress syndrome, crush syndrome, visceral injury, head injury, and bacterial infection is highly dependent on the ICU. The statistics of the casualty in the Hanshin-Awaji earthquake show that serious casualties accounted for 21% of the casualties. Takada and Otomo [143] calculated the number of casualties and hospital beds in the Nepal earthquake. Although all intensive care units and intensive care beds are provided for the seriously injured, there is a shortage of 15,053 beds for earthquake medical assistance. According to medical rescue at Christchurch Hospital Medical Rescue Clinic in the 2011 Christchurch earthquake, a generator failure caused power supplies to be cut off in important medical departments such as ICUs, which forced patients to undergo medical evacuation [144]. Due to a lot of health facilities being destroyed in the 2015 Nepal earthquake, there is a serious shortage of beds in the intensive care unit. The temporary secondary care beds have to be temporarily reconstructed for ICU. Moreover, there are still a large number of casualties that cannot get a medical rescue in the ICU, which leads the injured to become more seriously ill and even death [145].

By analyzing the process of postearthquake medical rescue, it can be found that the key points of medical rescue at different stages are different. In different medical rescue stages (e.g., medical diagnosis, emergency treatment, and intensive care), there are differences in the components that affect resilience of the healthcare system. The postearthquake functional performance of the medical equipment is the key in affecting the efficiency of medical diagnosis. The key to improving emergency treatment functionality is the integrity of medical devices and system modeling strategies. The key to improving the seismic resilience of intensive care lies in the safety of building structures and system modeling strategies. Therefore, mathematical modeling also becomes the key to improve the medical rescue process.

6. The Key Points of Seismic Resilience of Healthcare

6.1. Seismic Performance of Medical Equipment. The seismic vulnerability of medical equipment is an indispensable part of the seismic resilience analysis of healthcare systems. However, the research standards on the seismic vulnerability of medical equipment and its dynamic response characteristics under seismic action are not uniform, which lead to large deviations in the experimental data. Seismic vulnerability data for medical devices are also not included in standards such as FEMA P58 [146] and GB/T 38591-2020 [147]. Therefore, data for medical devices come from experiments. Table 6 shows the seismic performance of the medical equipment in experiments.

The research on medical devices using uniform standards. The seismic response and seismic damage of different types of equipment were investigated. The corresponding seismic vulnerability model was established to provide basic data for the evaluation of the seismic resilience of healthcare systems.

6.2. Functional Resilience Modeling Methods for Healthcare Systems. The purpose of studying the seismic resilience of the healthcare system is to improve the medical ability of the healthcare system to cope with earthquakes and ensure the effective function of the healthcare system after the earthquake. By collating the literature on postearthquake medical processes, it is found that systematic modeling and analysis of medical processes can improve the efficiency of medical functions. At present, the functional modeling methods of healthcare systems mainly include discrete event modeling, system dynamics modeling, and subject modeling.

Discrete event (DE) systems are dynamic systems that evolve from asynchronous bursty event-driven states. The

Table 5: Postearthquake application cases of medical equipment.

Authors	Medical devices	Sample	Earthquake name
Zhao et al. [100]	CT (computed tomography), X-ray, and color doppler	1871	2008 Sichuan earthquake
Chu et al. [130]	16-slice multidetector CT scanner	221	2008 Sichuan earthquake
Dong et al. [131]	Multislice spiral CT	215	2008 Sichuan earthquake
Dan et al. [132]	Ultrasound equipment and radiological equipment	3307	2008 Sichuan earthquake
Banaste et al. [133]	CT	2354	2010–2016 France
Yu et al. [134]	Portable color doppler	—	2008 Sichuan earthquake
Ahmad et al. [135]	Ultrasound equipment	87	2015 Pakistan earthquake
Dan et al. [136]	Ultrasound equipment	1207	2008 Sichuan earthquake
Iyama et al. [137]	Digital radiography (DR), computed tomography (CT), and magnetic resonance imaging (MRI)	3483–4225	2016 Kumamoto earthquake

Table 6: Seismic performance testing of medical equipment.

Authors	Medical equipment	Test	Conclusion
Konstantinidis and Makris [148]	Cabinet equipment	Static test	The seismic vulnerability curve of equipment under different slip limits is given by probabilistic seismic demand model fitting
Costa et al. [149]	Medical medicine cabinets, medicines	Shake table test	Three damage states of the medicine cabinet are defined as follows: residual displacement of more than 20 mm, rocking, and overturning. Built-in drugs have two damage states: overturning and crushing
Kuo et al. [150]	Medicine rack	Shake table test	The distance between the drug on the shelf falling on the ground and the medicine shelf was used to describe the mixing degree of the medicine rack after the earthquake
Shang et al. [57]	Infusion stents, medicine cabinets, ambulances, hospital beds, and medical shadowless lamps	Shake table test	The corresponding seismic fragility curves of the hospital cabinets under different damage states were developed based on experimental data
Nikfar and Konstantinidis [151]	Wheels/castors support medical equipment	Shake table test	Contour plots are proposed that specify the displacement, velocity, and acceleration accuracy of vision-based measurements, which can be used in future applications
Nikfar and Konstantinidis [152]	Wheels/castors support medical equipment	Shake table test	It was concluded that, in base-isolated buildings, locking the wheels/casters on ECs reduces EC response. Fragility curves were developed for mobile ECs on unlocked wheels and casters in base-isolated buildings
Nikfar and Konstantinidis [153]	Ultrasonic equipment cart carries small equipment	Shake table test	Appropriate structural engineering demand parameters associated with the relative displacement and relative velocity demands of the equipment are proposed and used to develop conditional probability curves. Finally, in an effort to extend the results of this experimental study to similar equipment on wheels/casters, the performance of a simple numerical model in predicting the peak seismic demands is evaluated

Table 7: The analysis method of functional resilience of the hospital.

	Authors	Casualty classification	Healthcare resource variables	Optimizing the results
DEs	Lowery [155]	Classification of severely ill wounded	Procedures for the presentation of critically ill patients, particularly surgery and ICU	Optimizing the timing of visits for casualty patients in different types of intensive care units
	Swisher et al. [156]	All the wounded	Number of caregivers	The average length of time for a casualty visit with a different number of nursing staff
	Yi et al. [157]	Patients are divided according to the type of disease	The time of treatment of the wounded in each department	The process of visits for patients with different diseases has been improved to reduce the waiting time for the casualty
	Cimellaro et al. [61]	The severity of the wounded is divided into white, yellow, green, and white from low to high	Medical resources occupied by casualty patients with different injuries (emergency rooms, ICU)	The model simulates the waiting time of casualty patients with different hospital attendance rates under different seismic intensity and analyzes the difference in waiting time of casualty patients with different emergency plans
	Basaglia et al. [158]	All the wounded	Emergency, hospitalization, and doctor	The two models are defined by balancing the need to represent a complex system with sufficient accuracy, the limitations posed by data availability, and the multiplicity of outcomes of patient treatment
	Shahverdi et al. [159]	All the wounded	—	Discrete modeling from patient arrival patterns, impacts on resources, and effects on unit capacities/capabilities to assess hospital system resilience to disaster events involving physical damage and demand surge
ABMs	Kaushal et al. [160]	Emergency casualty	Healthcare workers and hospital beds	The efficiency of emergency fast-track reception has been improved, and the waiting time for the injured has been optimized
	Taboada et al. [161]	Emergency casualty	Healthcare workers and medical equipment	The model optimizes the waiting time, treatment time, and number of patients treated for the injured in the emergency department
	Cimellaro et al. [60]	All the wounded	Ambulances, hospital networks, and road networks	Optimized the casualty transport process
SD	Diaz et al. [162]	All the wounded	Healthcare workers	Combined with the relationship between medical supply and demand, the situation of different workloads is studied, and the doctor's work efficiency method is optimized
	Cassettari et al. [163]	All the wounded	Sickbed	Effect of treatment time on bed resources
	Hirsch [164]	All the wounded	Treatment process and infrastructure	The impact of infrastructure failures on the treatment process
	Arboleda et al. [165]	All the wounded	Hospital beds, doctors, medicines, and infrastructure	The impact of different casualty attendance rates or different infrastructure failures on the number of wounded waiting for treatment in each department
	Khanmohammadi et al. [62]	All the wounded	Healthcare buildings and infrastructure	The impact of hospital building and infrastructure repair on the proportion of wounded

state of the system usually only takes a limited number of discrete values, corresponding to the quality of system components, the number of workpieces to be processed, or the situation of macro management such as planning and job scheduling. These state changes are caused by the occurrence of various events such as the appearance or disappearance of certain environmental conditions and the start or completion of system operations. Discrete event modeling in healthcare systems is primarily based on the medical process of the patient. It is a completely discrete event from the beginning of the injured entering the hospital to the end of the injured exiting the hospital. A large number of wounded people experienced the above process after the earthquake. However, the medical capacity of the hospital is limited. The wounded have to queue up for treatment. Therefore, the waiting time for the wounded will become longer. Mathematical modeling is used to calculate the visit time of patients or the use of medical resources (e.g., emergency departments and ICUs), and then propose strategies to improve hospital operation efficiency and shorten the waiting time of the injured.

Agent-based models (ABMs) are a class of computational models used to simulate the behavior and interactions of autonomous agents (individual or collective entities) to assess their impact on the system. It combines elements of game theory, complex systems, emergence, computational sociology, multiagent systems, and evolutionary programming. The Monte Carlo method is used to introduce randomness. This modeling method is mostly used in the healthcare system in the transmission of diseases and the operation process of the hospital and can also be used for the simulation and analysis of the treatment process of the injured in the hospital. Doctors and the wounded are usually taken as the subjects. And the behaviors emerging from the subjects are further explored through the analysis of the interaction between the subjects.

System dynamics (SD) was first proposed by Forrester [154]; different systems have unique structural systems. Moreover, according to the idea of system science, the system function is determined by the system structure. The problems of system function arise from the interaction between structural components, which is not affected by external interference or random events. Therefore, system dynamics is widely used in hospital functional modeling.

Combining the therapeutic behavior and influencing factors of each component of the treatment process, the moldings study the impact of individual behavior on system behavior. Table 7 shows the specific applications of the three types of modeling methods in healthcare systems. DEDs are more focused on the flow of events. ABMs are more concerned with the impact of individual attributes and behaviors on the system. The SD method focuses more on the interaction between the internal elements of the system and the change of flow. Combined with the postearthquake treatment process, appropriate modeling methods were selected to improve the resilience of all aspects of the healthcare system.

7. Conclusion

This article reviews and summarizes the concepts of resilience, healthcare systems, and the resilience of the healthcare system. The concept of resilience has shown its application prospects in many fields. And the advantages of improving system robustness, rapid recovery, and resource redundancy are obvious. The concept of resilience was introduced into the healthcare system. Its quantitative analysis methods were introduced.

According to the literature review, the main findings of this study are as follows: the application effect of resilience theory in different systems clarifies the key to resilience analysis. The medical system introduces resilience theory to improve its earthquake relief performance. The quantification of the function of the medical system becomes the key to the quantitative analysis of its seismic resilience.

Meanwhile, an understanding of the characteristics of medical demands due to earthquakes is fundamental for effective medical rescue and reasonable allocation of medical resources and is also beneficial for rapid injury triage and prompt treatment. Increased knowledge of the injury characteristics of patients hospitalized following seismic disasters plays an important role in summarizing experiences and lessons, improving our ability to deal with destructive disasters, and helping the effective and reasonable organization of medical rescue systems for future disasters. The profile of these injuries may also provide valuable information for injury interventions, including rehabilitation, psychological treatment, economic cost assessment, and planning for future earthquake disasters.

This article reviews the postearthquake medical rescue process and explores the key points affecting the medical rescue function in the medical rescue process. Combined with the medical rescue process, the application of seismic toughness in the medical system is discussed. Numerical analysis of medical device vulnerability and system function is applied to the seismic toughness analysis of medical systems.

The efficiency of postearthquake medical rescue is reflected in the efficiency of each medical link in the medical rescue process and the smoothness of the cooperation of each medical link. Therefore, the key to the seismic resilience analysis of the healthcare system lies in the key factors affecting the treatment efficiency of each medical link and the simulation analysis of the smoothness of the cooperation of each medical link. Earthquakes will continue to strike and the healthcare system must be prepared to overcome the resulting situations by anticipating consequences and planning accordingly.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

[1] Em-Dat, "The international disasters database centre for research on the epidemiology of disasters," 2021, https://www.emdat.be/.

[2] M. Tembe, S. Dhakal, A. Shrestha, J. Mugele, and D. R. House, "Impact of Nepal earthquake on patients presenting for emergency care at patan hospital," *Disaster Medicine and Public Health Preparedness*, vol. 13, no. 02, pp. 211–216, 2019.

[3] L. A. Ellis, K. Churruca, R. Clay-Williams et al., "Patterns of resilience: a scoping review and bibliometric analysis of resilient health care," *Safety Science*, vol. 118, pp. 241–257, 2019.

[4] K. Şeşetyan, M. B. Demircioğlu Tümsa, and A. Akinci, "Evaluation of the seismic hazard in the marmara region (Turkey) based on updated databases," *Geosciences*, vol. 9, no. 12, p. 489, 2019.

[5] J. Jiang, Y. P. Li, M. Y. Wang, and C. M. Mo, "Comparison of Yushu earthquake and wenchuan earthquake in medical rescue," *Chinese Journal of Evidence-Based Medicine*, vol. 10, no. 5, pp. 550–554, 2010.

[6] M. Hauswald, M. E. Richards, N. L. Kerr, T. A. Schmidt, and T. Helderman, "The Haitian earthquake and academic emergency medicine," *Academic Emergency Medicine*, vol. 17, no. 7, pp. 762–764, 2010.

[7] X. Liu, *Empirical Study and Modeling of Medical Evacuation System Following a Major Earthquake*, Naval Medical University China, 2012.

[8] World Health Organization, *A Strategic Framework for Emergency Preparedness*, WHO Geneva, Switzerland, 2017.

[9] Pan-American Health Organization and World Health Organization, "Resolution CD50.R15: plan of action of safe hospitals," in *50th Directory Council, 62nd Session of the Regional Committee*, PAHO Washington, D.C., USA, 2011.

[10] WCDR, "Hyogo Framework for Action 2005-2015: Building the Resilience of Nations and Communities to Disasters," in *Proceedings of the World Conference on Disaster Reduction*, pp. 18–22, Hyogo, Japan, January 2005.

[11] WCDR, "Sendai Framework for Disaster Risk Reduction 2015 – 2030," in *Proceedings of the World Conference on Disaster Reduction*, Sendai, Japan, March 2015.

[12] M. Gerdin, A. Wladis, and J. von Schreeb, "Foreign field hospitals after the 2010 Haiti earthquake: how good were we?" *Emergency Medicine Journal*, vol. 30, no. 1, 2013.

[13] E. D. Vugrin, D. E. Warren, and M. A. Ehlen, "A framework for assessing the resilience of infrastructure and economic systems," in *Sustainable and Resilient Critical Infrastructure Systems*, K. Gopalakrishnan and S. Peeta, Eds., pp. 77–116, Springer, Berlin, Germany, 1st edition, 2010.

[14] J. M. Blackmore and R. a. J. Plant, "Risk and resilience to enhance sustainability with application to urban water systems," *Journal of Water Resources Planning and Management*, vol. 134, no. 3, pp. 224–233, 2008.

[15] M. Keck and P. Sakdapolrak, "What is social resilience? Lessons learned and ways forward," *Erdkunde*, vol. 67, no. 1, pp. 5–19, 2013.

[16] R. J. T. Klein, R. J. Nicholls, and F. Thomalla, "Resilience to natural hazards: how useful is this concept," *Environmental Hazards*, vol. 5, no. 1, pp. 35–45, 2003.

[17] J. M. Anderies, "Robustness, institutions, and large-scale change in social-ecological systems: the hohokam of the phoenix basin," *Journal of Institutional Economics*, vol. 2, no. 2, pp. 133–155, 2006.

[18] K. Tierney and M. Bruneau, "Conceptualizing and measuring resilience: a key to disaster loss reduction," *TR News*, vol. 5, no. 250, pp. 14-15, 2007.

[19] D. Wei and K. Ji, "Resilient Industrial Control System (Rics): Concepts, Formulation, Metrics, and Insights," in *Proceedings of the 3rd International Symposium on Resilient Control Systems*, pp. 15–22, Idaho Falls, ID, USA, January 2010.

[20] S. Somers, "Measuring resilience potential: an adaptive strategy for organizational crisis planning," *Journal of Contingencies and Crisis Management*, vol. 17, no. 1, pp. 12–23, 2009.

[21] D. Harper, "Online etymology dictionary," 2021, https://www.etymonline.com/.

[22] C. S. Holling, "Resilience and stability of ecological systems," *Annual Review of Ecology and Systematics*, vol. 4, pp. 1–23, 1973.

[23] A. B. Wildavsky, "Searching for safety," *Journal of Risk & Insurance*, vol. 57, no. 3, p. 564, 1990.

[24] D. S. Mileti, *Disasters by Design: A Reassessment of Natural Hazards in the United States*, Joseph Henry Press, Washington, DC, USA, 1999.

[25] L. K. Comfort, "Taking complexity seriously: policy analysis, triangulation, and sustainable development," *Journal of Policy Analysis and Management*, vol. 18, no. 1, pp. 181–184, 1999.

[26] W. N. Adger, "Social and ecological resilience: are they related," *Progress in Human Geography*, vol. 24, no. 3, pp. 347–364, 2000.

[27] M. Bruneau, S. E. Chang, R. T. Eguchi et al., "A framework to quantitatively assess and enhance the seismic resilience of communities," *Earthquake Spectra*, vol. 19, no. 4, pp. 733–752, 2003.

[28] B. Walker, C. S. Holling, S. R. Carpenter, and A. P. Kinzig, "Resilience, adaptability and transform ability in social-ecological systems," *Ecology and Society*, vol. 9, no. 2, p. 5, 2004.

[29] B. Walker and D. Salt, *Resilience Thinking: Sustaining Ecosystems And People In A Changing World*, Island press, Washington, DC, USA, 2006.

[30] B. Allenby and J. Fink, "Toward inherently secure and resilient societies," *Science*, vol. 309, no. 5737, pp. 1034–1036, 2005.

[31] U S Department of Homeland Security, *National Infrastructure Protection Plan*, US Department of Homeland Security, Washington, DC, USA, 2006.

[32] C. Wamsler, "Bridging the gaps: stakeholder-based strategies for risk reduction and financing for the urban poor," *Environment and Urbanization*, vol. 19, no. 1, pp. 115–142, 2007.

[33] UNISDR, *Terminology on Disaster Risk Reduction*, UNDRR, Geneva, Switzerland, 2009.

[34] United Nations, *Disaster Risk Reduction Terminology*, UNDRR, Geneva, Switzerland, 2009.

[35] O. Cohen, D. Leykin, M. Lahad, A. Goldberg, and L. Aharonson-Daniel, "The conjoint community resiliency assessment measure as a baseline for profiling and predicting

community resilience for emergencies," *Technological Forecasting and Social Change*, vol. 80, no. 9, pp. 1732–1741, 2013.
[36] Resilience Alliance, "Resilience [EB/OL]," 2022, http://www.resiience.org/index.php/resilience.
[37] C. Folke, "Resilience: the emergence of a perspective for social-ecological systems analyses," *Global Environmental Change*, vol. 16, no. 3, pp. 253–267, 2006.
[38] World Health Organization, *The World Health Report 2000: Health Systems Improving Performance*, WHO, Geneva, Switzerland, 2000.
[39] O. A. S. P. R. Office of the assistant secretary for preparedness and response, *Healthcare Preparedness Capabilities: National Guidance For Healthcare System Preparedness*, U.S. department of health and human services, Washington, DC, USA, 2012.
[40] G. H. Wu, Y. X. Zang, and Y. X. Liu, *Chinese Dictionary of Health Management*, China Science and Technology Press, Beijing, China, 2001.
[41] M. P. Kieny and D. Dovlo, "Beyond Ebola: a new agenda for resilient health systems," *The Lancet*, vol. 385, no. 9963, pp. 91-92, 2015.
[42] E. W. Barasa, K. Cloete, and L. Gilson, "From bouncing back, to nurturing emergence: reframing the concept of resilience in health systems strengthening," *Health Policy and Planning*, vol. 32, no. 3, pp. 91–94, 2017.
[43] M. E. Kruk, M. Myers, S. T. Varpilah, and B. T. Dahn, "What is a resilience health system? Lessons from ebola," *The Lance*, vol. 285, no. 9980, pp. 1910–1912, 2015.
[44] K. Blanchet, S. L. Nam, B. Ramalingam, and F. Pozo-Martin, "Governance and capacity to manage resilience of health systems: towards a new conceptual framework," *International Journal of Health Policy and Management*, vol. 6, no. 8, pp. 431–435, 2017.
[45] S. Zhong, M. Clark, X. Y. Hou, Y. L. Zang, and G. Fitzgerald, "Development of hospital disaster resilience: conceptual framework and potential measurement," *Emergency Medicine Journal*, vol. 31, no. 11, pp. 930–938, 2014.
[46] G. P. Cimellaro and M. Pique, "Resilience of a hospital emergency department under seismic event," *Advances in Structural Engineering*, vol. 19, no. 5, pp. 825–836, 2016.
[47] World Health Organization, *Operational Framework for Building Climate Resilience Health Systems*, WHO, Geneva, Switzerland, 2015.
[48] C. C. Jacques, J. McIntosh, S. Giovinazzi, T. D. Kirsch, T. Wilson, and J. Mitrani-Reiser, "Resilience of the canterbury hospital system to the 2011 Christchurch earthquake," *Earthquake Spectra*, vol. 30, no. 1, pp. 533–554, 2014.
[49] S. H. Ramandi and H. Kashani, "A framework to evaluate the resilience of hospital networks," in *Proceedings of the creative construction conference*, Ljubljana, Slovenia, June 2018.
[50] S. H. Berg and K. Aase, *Resilient Characteristics as Described in Empirical Studies on Health Care*, SpringerBriefs in Applied Sciences and Technology, Berlin, Germany, 2019.
[51] S. Wiig, K. Aase, S. Billett et al., "Defining the boundaries and operational concepts of resilience in the resilience in healthcare research program," *BMC Health Services Research*, vol. 20, no. 1, p. 330, 2020.
[52] H. B. Lyng, C. Macrae, V. Guise et al., "Balancing adaptation and innovation for resilience in healthcare – a metasynthesis of narratives," *BMC Health Services Research*, vol. 21, no. 1, p. 759, 2021.
[53] S. S. Pei, C. H. Zhai, Z. Q. Wang, K. Z. Liu, and J. Hu, "Resilience assessment of the interdependent transportation–healthcare system during emergency response," *Structure and Infrastructure Engineering*, 2022.
[54] H. Cai, N. S. N. Lam, Y. Qiang, L. Zou, R. M. Correll, and V. Mihunov, "A synthesis of disaster resilience measurement methods and indices," *International Journal of Disaster Risk Reduction*, vol. 31, pp. 844–855, 2018.
[55] Pan American Health Organization, *Hospital Safety index: Guide for Evaluators*, PAHO, Washington, DC, USA, 2008.
[56] S. Zhong, M. Clark, X. Y. Hou, Y. Zang, and G. FitzGerald, "Development of key indicators of hospital resilience: a modified Delphi study," *Journal of Health Services Research and Policy*, vol. 20, no. 2, pp. 74–82, 2015.
[57] Q. X. Shang, J. C. Li, C. B. Du, and T. Wang, "Seismic fragility analysis of freestanding hospital cabinets based on shaking table tests," *Journal of Earthquake Engineering*, pp. 1–20, 2022.
[58] S. Yavari, S. E. Chang, and K. Elwood, "Modeling post-earthquake functionality of regional health care facilities," *Earthquake Spectra*, vol. 26, no. 3, pp. 869–892, 2010.
[59] G. P. Cimellaro, A. M. Reinhorn, and M. Bruneau, "Seismic resilience of a hospital system," *Structure and Infrastructure Engineering*, vol. 6, no. 1–2, pp. 127–144, 2010.
[60] G. P. Cimellaro, V. Arcidiacono, A. M. Reinhorn, and M. Bruneau, "Disaster resilience of hospitals considering emergency ambulance services," in *Proceedings of the structures congress*, pp. 2824–2836, Pittsburgh, PA, USA, May 2013.
[61] G. P. Cimellaro, M. Malavisi, and S. Mahin, "Using discrete event simulation models to evaluate resilience of an emergency department," *Journal of Earthquake Engineering*, vol. 21, no. 2, pp. 203–226, 2017.
[62] S. Khanmohammadi, H. Farahmand, and H. Kashani, "A system dynamics approach to the seismic resilience enhancement of hospitals," *International Journal of Disaster Risk Reduction*, vol. 31, pp. 220–233, 2018.
[63] N. Liguori, N. Tarque, C. Bambarén, E. Spacone, W. Viveen, and G. de Filippo, "Hospital treatment capacity in case of seismic scenario in the Lima Metropolitan area, Peru," *International Journal of Disaster Risk Reduction*, vol. 38, Article ID 101196, 2019.
[64] L. Ceferino, J. Mitrani-Reiser, A. Kiremidjian, G. Deierlein, and C. Bambaren, "Effective plans for hospital system response to earthquake emergencies," *Nature Communications*, vol. 11, no. 1, 2020.
[65] E. M. Hassan and H. Mahmoud, "An integrated socio-technical approach for post-earthquake recovery of interdependent healthcare system," *Reliability Engineering & System Safety*, vol. 201, Article ID 106953, 2020.
[66] J. Liu, C. H. Zhai, and P. Yu, "A probabilistic framework to evaluate seismic resilience of hospital buildings using bayesian networks," *Reliability Engineering & System Safety*, vol. 226, Article ID 108644, 2022.
[67] Denver Health, *National Hospital Available Beds for Emergencies and Disasters (HAvBED) System: Final Report*, AHRQ Publication, Rockville, MD, USA, 2005.
[68] E. M. Hassan and H. Mahmoud, "An integrated socio-technical approach for post-earthquake recovery of interdependent healthcare system," *Reliability Engineering & System Safety*, vol. 201, Article ID 106953, 2020.
[69] C. H. Zhai, P. Yu, and W. P. Wen, "A physical-organizational method for the functionality assessment of A hospital subjected to earthquakes," *Journal of Earthquake Engineering*, vol. 26, no. 14, pp. 7119–7139, 2022.

[70] K. H. Dansky and J. Miles, "Patient satisfaction with ambulatory healthcare services: waiting time and filling time," *Hospital & Health Services Administration*, vol. 42, pp. 165–177, 1997.

[71] W. F. Shen, L. B. Jiang, and X. J. He, "Precision augmentation of medical surge capacity for disaster response," *Emergency Medicine International*, vol. 2020, Article ID 5387043, 6 pages, 2020.

[72] S. Kato, Y. Yamaguchi, and I. Kawachi, "Assessment of community vulnerability and medical surge capacity in a foreseeable major disaster," *PLoS One*, vol. 15, no. 7, 2020.

[73] B. H. Tang, Q. Chen, X. Chen et al., "Earthquake-related injuries among survivors: a systematic review and quantitative synthesis of the literature," *International Journal of Disaster Risk Reduction*, vol. 21, pp. 159–167, 2017.

[74] H. K. Armenian, A. Melkonian, E. K. Noji, and A. P. Hovanesian, "Deaths and injuries due to the earthquake in Armenia: a cohort approach," *International Journal of Epidemiology*, vol. 26, no. 4, pp. 806–813, 1997.

[75] X. D. Bai and X. H. Liu, "Retrospective analysis: the earthquake-injured patients in Barakott of Pakistan," *Chinese Journal of Traumatology*, vol. 12, no. 2, pp. 122–124, 2009.

[76] S. A. Dhar, M. A. Halwai, M. R. Mir et al., "The Kashmir earthquake experience," *European Journal of Trauma and Emergency Surgery*, vol. 33, no. 1, pp. 74–80, 2007.

[77] K. Milch, Y. Gorokhovich, and S. Doocy, "Effects of seismic intensity and socioeconomic status on injury and displacement after the 2007 Peru earthquake," *Disasters*, vol. 34, no. 4, pp. 1171–1182, 2010.

[78] M. J. Emami, A. R. Tavakoli, H. Alemzadeh et al., "Strategies in evaluation and management of bam earthquake victims," *Prehospital and Disaster Medicine*, vol. 20, no. 5, pp. 327–330, 2005.

[79] A. Farfel, A. Assa, I. Amir et al., "Haiti earthquake 2010: a field hospital pediatric perspective," *European Journal of Pediatrics*, vol. 170, no. 4, pp. 519–525, 2011.

[80] P. Hatamizadeh, I. Najafi, R. Vanholder et al., "Epidemiologic aspects of the bam earthquake in Iran: the nephrologic perspective," *American Journal of Kidney Diseases*, vol. 47, no. 3, pp. 428–438, 2006.

[81] S. H. İskit, H. Alpay, H. Tuğtepe et al., "Analysis of 33 pediatric trauma victims in the 1999 Marmara, Turkey earthquake," *Journal of Pediatric Surgery*, vol. 36, no. 2, pp. 368–372, 2001.

[82] V. Jain, R. Noponen, and B. M. Smith, "Pediatric surgical emergencies in the setting of a natural disaster: experiences from the 2001 earthquake in Gujarat, India," *Journal of Pediatric Surgery*, vol. 38, no. 5, pp. 663–667, 2003.

[83] H. S. Jian, Z. m. Lü, and Y. Y. Li, "Epidemiological investigation on Wenchuan earthquake-struck trauma patients admitted to two hospitals of Chongqing," *Chinese Journal of Traumatology*, vol. 13, no. 2, pp. 101-102, 2010.

[84] Y. Kuwagata, J. Oda, H. Tanaka et al., "Analysis of 2,702 traumatized patients in the 1995 hanshin-awaji earthquake," *The Journal of Trauma, Injury, Infection, and Critical Care*, vol. 43, no. 3, pp. 427–432, 1997.

[85] H. A. Mohebbi, S. Mehrvarz, M. Saghafinia et al., "Earthquake related injuries: assessment of 854 victims of the 2003 Bam disaster transported to tertiary referral hospitals," *Prehospital and Disaster Medicine*, vol. 23, no. 6, pp. 510–515, 2008.

[86] J. M. Mulvey, S. U. Awan, A. A. Qadri, and M. A. Maqsood, "Profile of injuries arising from the 2005 Kashmir Earthquake: the first 72h," *Injury*, vol. 39, no. 5, pp. 554–560, 2008.

[87] S. Parasuraman, "The impact of the 1993 Latur-Osmanabad (Maharashtra) earthquake on lives, livelihoods and property," *Disasters*, vol. 19, no. 2, pp. 156–169, 1995.

[88] C. Peek-Asa, M. Ramirez, H. Seligson, and K. Shoaf, "Seismic, structural, and individual factors associated with earthquake related injury," *Injury Prevention*, vol. 9, no. 1, pp. 62–66, 2003.

[89] S. Poçan, M. S. Özkan, M. M. Hulusi Us, M. O. Çakir, and M. Gökben, "Crush syndrome and acute renal failure in the marmara earthquake," *Military Medicine*, vol. 167, no. 6, pp. 516–518, 2002.

[90] J. E. Pointer, J. Michaelis, C. Saunders et al., "The 1989 loma prieta earthquake: impact on hospital patient care," *Annals of Emergency Medicine*, vol. 21, no. 10, pp. 1228–1233, 1992.

[91] M. C. Roces, M. E. White, M. M. Dayrit, and M. E. Durkin, "Risk factors for injuries due to the 1990 earthquake in Luzon, Philippines," *Bulletin of the World Health Organization*, vol. 70, no. 4, pp. 509–514, 1992.

[92] N. Roy, H. Shah, V. Patel, and R. R. Coughlin, "The Gujarat earthquake (2001) experience in a seismically unprepared area: community hospital medical response," *Prehospital and Disaster Medicine*, vol. 17, no. 4, pp. 186–195, 2002.

[93] M. Sabzehchian, H. Abolghasemi, M. H. Radfar, N. Jonaidi-Jafari, H. Ghasemzadeh, and F. M. Burkle, "Pediatric trauma at tertiary-level hospitals in the aftermath of the bam, Iran earthquake," *Prehospital and Disaster Medicine*, vol. 21, no. 5, pp. 336–339, 2006.

[94] C. Salinas, C. Salinas, and J. Kurata, "The effects of the Northridge earthquake on the pattern of emergency department care," *The American Journal of Emergency Medicine*, vol. 16, no. 3, pp. 254–256, 1998.

[95] K. I. Shoaf, H. R. Sareen, L. H. Nguyen, and L. B. Bourque, "Injuries as a result of California earthquakes in the past decade," *Disasters*, vol. 22, no. 3, pp. 218–235, 1998.

[96] H. Tanaka, J. Oda, A. Iwai et al., "Morbidity and mortality of hospitalized patients after the 1995 Hanshin-Awaji earthquake," *The American Journal of Emergency Medicine*, vol. 17, no. 2, pp. 186–191, 1999.

[97] N. Uzun, F. K. Savrun, and M. E. Kiziltan, "Electrophysiologic evaluation of peripheral Nerve injuries in children following the marmara earthquake," *Journal of Child Neurology*, vol. 20, no. 3, pp. 207–212, 2005.

[98] C. Yang, H. Y. Wang, H. J. Zhong et al., "The epidemiological analyses of trauma patients in Chongqing teaching hospitals following the Wenchuan earthquake," *Injury*, vol. 40, no. 5, pp. 488–492, 2009.

[99] L. Zhang, H. Li, J. R. Carlton, and R. Ursano, "The injury profile after the 2008 earthquakes in China," *Injury*, vol. 40, no. 1, pp. 84–86, 2009.

[100] L. P. Zhao, J. M. Rodriguez-Llanes, W. Qi et al., "Multiple injuries after earthquakes: a retrospective analysis on 1,871 injured patients from the 2008 wenchuan earthquake," *Critical Care*, vol. 16, no. 3, pp. 1–9, 2012.

[101] P. Kang, L. Zhang, W. Liang et al., "Medical evacuation management and clinical characteristics of 3,255 inpatients after the 2010 Yushu earthquake in China," *Journal of Trauma and Acute Care Surgery*, vol. 72, no. 6, pp. 1626–1633, 2012.

[102] S. Ding, Y. H. Hu, Z. K. Zhang, and T. Wang, "A contrast study of the traumatic condition between the wounded in 5.12 Wenchuan earthquake and 4.25 Nepal earthquake,"

Chinese Journal of Traumatology, vol. 18, no. 3, pp. 157–160, 2015.

[103] J. Wen, X. Sun, Y. Shi 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," *European Journal of Trauma and Emergency Surgery*, vol. 38, no. 3, pp. 261–267, 2012.

[104] L. Zhang, M. Zhao, W. Fu et al., "Epidemiological analysis of trauma patients following the lushan earthquake," *PLoS One*, vol. 9, no. 5, 2014.

[105] P. Kang, B. Tang, Y. Liu et al., "Medical efforts and injury patterns of military hospital patients following the 2013 lushan earthquake in China: a retrospective study," *International Journal of Environmental Research and Public Health*, vol. 12, no. 9, pp. 10723–10738, 2015.

[106] Z. X. Hu, X. X. Zeng, P. Fu et al., "Predictive factors for acute renal failure in crush injuries in the Sichuan earthquake," *Injury*, vol. 43, no. 5, pp. 613–618, 2012.

[107] T. Li, X. Y. Jiang, H. Chen, Z. Yang, X. B. Wang, and M. Y. Wang, "Orthopaedic injury analysis in the 2010 Yushu, China earthquake," *Injury*, vol. 43, no. 6, pp. 886–890, 2012.

[108] S. Doocy, G. Jacquet, M. Cherewick, and T. D. Kirsch, "The injury burden of the 2010 Haiti earthquake: a stratified cluster survey," *Injury*, vol. 44, no. 6, pp. 842–847, 2013.

[109] J. Qiu, G. D. Liu, S. X. Wang et al., "Analysis of injuries and treatment of 3 401 inpatients in 2008 Wenchuan earthquake—based on Chinese Trauma Databank," *Chinese Journal of Traumatology*, vol. 13, no. 5, pp. 297–303, 2010.

[110] J. Gu, W. Yang, J. Cheng et al., "Temporal and spatial characteristics and treatment strategies of traumatic brain injury in Wenchuan earthquake," *Emergency Medicine Journal*, vol. 27, no. 3, pp. 216–219, 2010.

[111] Z. Fan, A. Li, B. Lian et al., "Injury types of victims in the 12th May 2008 Wenchuan earthquake: analysis of 1,038 patients in Jiangyou City," *European Journal of Trauma and Emergency Surgery*, vol. 37, no. 1, pp. 3–7, 2011.

[112] C. H. Lin, W. H. Chang, C. L. Wu, S. T. Pan, and C. H. Chi, "Medical response to 2016 earthquake in Taiwan," *The Lancet*, vol. 388, no. 10040, pp. 129-130, 2016.

[113] W. Li, J. Qian, X. F. Liu et al., "Management of severe crush injury in a front-line tent ICU after 2008 Wenchuan earthquake in China: an experience with 32 cases," *Critical Care*, vol. 13, no. 6, 2009.

[114] Y. Li, F. Pan, and Y. Li, "Analysis of rehabilitation needs, measures taken, and their effectiveness for the wounded following the Wenchuan Earthquake," *Journal of Evidence-Based Medicine*, vol. 2, no. 4, pp. 258–264, 2009.

[115] D. Johnston, S. Standring, K. Ronan et al., "The 2010/2011 Canterbury earthquakes: context and cause of injury," *Natural Hazards*, vol. 73, no. 2, pp. 627–637, 2014.

[116] Y. Xu, J. Huang, J. Zhou, and Y. Zeng, "Patterns of abdominal injury in 37 387 disaster patients from the Wenchuan earthquake," *Emergency Medicine Journal*, vol. 30, no. 7, pp. 538–542, 2013.

[117] X. Liu, Y. Y. Liu, S. H. Liu, X. R. Zhang, L. Du, and W. X. Huang, "Classification tree analysis of the factors influencing injury-related disability caused by the Wenchuan earthquake," *Journal of International Medical Research*, vol. 42, no. 2, pp. 487–493, 2014.

[118] S. Giri, K. Risnes, O. Uleberg et al., "Impact of 2015 earthquakes on a local hospital in Nepal: a prospective hospital-based study," *PLoS One*, vol. 13, no. 2, 2018.

[119] X. Chen, T. Yang, and J. Li, "Profile and management of musculoskeletal injuries associated with the Lushan Earthquake in 2013," *Disaster Medicine and Public Health Preparedness*, vol. 12, no. 3, pp. 408–410, 2018.

[120] E. M. Hassan and H. Mahmoud, "Full functionality and recovery assessment framework for a hospital subjected to a scenario earthquake event," *Engineering Structures*, vol. 188, pp. 165–177, 2019.

[121] B. Liang, J. Hou, and Z. He, "Rapid assessment method to assess vulnerability of structures using vulnerability index and disaster matrix," *Bulletin of Earthquake Engineering*, Springer, Berlin, Germany, 2023.

[122] X. Yao, B. Liang, B. Sun, D. Wang, and W. Gao, "Integrated disaster matrix and vulnerability index analyze the seismic performance of typical structures in rural villages in historical earthquakes," *Advances in Structural Engineering*, vol. 25, no. 14, pp. 2981–2997, 2022.

[123] J. L. Hick, J. A. Barbera, and G. D. Kelen, "Refining surge capacity: conventional, contingency, and crisis capacity," *Disaster Medicine and Public Health Preparedness*, vol. 3, no. 1, pp. S59–S67, 2009.

[124] G. D. Kelen and M. L. McCarthy, "The science of surge," *Academic Emergency Medicine*, vol. 13, no. 11, pp. 1089–1094, 2006.

[125] J. L. Hick, K. L. Koenig, D. Barbisch, and T. A. Bey, "Surge capacity concepts for health care facilities: the CO-S-TR model for initial incident assessment," *Disaster Medicine and Public Health Preparedness*, vol. 2, no. 1, pp. S51–S57, 2008.

[126] N. Achour, F. Pascale, A. D. F. Price et al., "Learning lessons from the 2011 Van Earthquake to enhance healthcare surge capacity in Turkey," *Environmental Hazards*, vol. 15, no. 1, pp. 74–94, 2016.

[127] M.-C. Therrien, J.-M. Normandin, and J.-L. Denis, "Bridging complexity theory and resilience to develop surge capacity in health systems," *Journal of Health, Organisation and Management*, vol. 31, no. 1, pp. 96–109, 2017.

[128] World Health Organization, *Disaster Risk Management for Health: Overview*, WHO, Geneva, Switzerland, 2011.

[129] Z. Liu, Z. Yang, Q. Lv et al., "Analysis of the three-tiered treatment model for emergency medical rescue services after the lushan earthquake," *Disaster Medicine and Public Health Preparedness*, vol. 12, no. 3, pp. 301–304, 2018.

[130] Z. G. Chu, Z. G. Yang, Z. H. Dong, T. W. Chen, Z. Y. Zhu, and H. Shao, "Comparative study of earthquake-related and non-earthquake-related head traumas using multidetector computed tomography," *Clinics*, vol. 66, no. 10, pp. 1735–1742, 2011.

[131] Z. H. Dong, Z. G. Yang, T. W. Chen et al., "Crush thoracic trauma in the massive sichuan earthquake: evaluation with multidetector ct of 215 cases," *Radiology*, vol. 254, no. 1, pp. 285–291, 2010.

[132] D. Dan, L. Mingsong, T. Jie et al., "Ultrasonographic applications after mass casualty incident caused by wenchuan earthquake," *The Journal of Trauma, Injury, Infection, and Critical Care*, vol. 68, no. 6, pp. 1417–1420, 2010.

[133] N. Banaste, B. Caurier, F. Bratan, J. F. Bergerot, V. Thomson, and I. Millet, "Whole-body CT in patients with multiple traumas: factors leading to missed injury," *Radiology*, vol. 289, no. 2, pp. 374–383, 2018.

[134] Z. H. Yu, H. J. Hu, D. L. Wang, and C. L. Song, "Application of mobile ultrasonoscope for fracture in earthquake rescue," *Journal of naval general hospital*, vol. 22, no. 02, pp. 78–80, 2009.

[135] F. Ahmad, M. Tariq, S. M. Abdul, A. R. Jamali, and A. Kausar, "Ultrasound imaging in settings of a natural disaster: experience from october 8th 2015 earthquake in Pakistan,"

Liaquat medical research journal, vol. 1, no. 2, pp. 35–39, 2019.

[136] D. Dan, L. Mingsong, T. Jie et al., "Ultrasonographic applications after mass casualty incident caused by wenchuan earthquake," *The Journal of Trauma, Injury, Infection, and Critical Care*, vol. 68, no. 6, pp. 1417–1420, 2010.

[137] A. Iyama, D. Utsunomiya, H. Uetani et al., "Emergency radiology after a massive earthquake: clinical perspective," *Japanese Journal of Radiology*, vol. 36, no. 11, pp. 641–648, 2018.

[138] J. H. Nieh, T. H. Hsu, H. C. Cheng, K. C. Chong, and P. F. Lai, "2018 taiwan hualien earthquake-disaster lessons we learned in the emergency department of a tertiary hospital," *Journal of Acute Medicine*, vol. 10, no. 4, pp. 149–155, 2020.

[139] X. Chu and Q. Zhong, "Post-earthquake allocation approach of medical rescue teams," *Natural Hazards*, vol. 79, no. 3, pp. 1809–1824, 2015.

[140] M. Shimada, A. Tanabe, M. Gunshin, R. H. Riffenburgh, and D. A. Tanen, "Resource utilization in the emergency department of a tertiary care university-based hospital in Tokyo before and after the 2011 Great East Japan earthquake and tsunami," *Prehospital and Disaster Medicine*, vol. 27, no. 6, pp. 515–518, 2012.

[141] Y. X. Lin, C. H. Lin, and C. H. Lin, "A challenge for healthcare system resilience after an earthquake: the crowdedness of a first-aid hospital by non-urgent patients," *PLoS One*, vol. 16, no. 4, 2021.

[142] X. B. Huang, Q. H. Guo, C. L. Li et al., "Intensive care unit treatment strategy and algorithm for critical patients from Lushan earthquake," *Zhonghua Yixue Zazhi*, vol. 94, no. 15, pp. 1130–1134, 2014.

[143] Y. Takada and Y. Otomo, "Study of medical demand-supply balance for the nankai trough earthquake," *Prehospital and Disaster Medicine*, vol. 35, no. 2, pp. 160–164, 2020.

[144] M. W. Ardagh, S. K. Richardson, V. Robinson et al., "The initial health-system response to the earthquake in Christchurch, New Zealand, in February, 2011," *The Lancet*, vol. 379, no. 9831, pp. 2109–2115, 2012.

[145] D. Aryal, S. P. Acharya, G. S. Shrestha, A. Goffi, and L. Hawryluck, "Nepal after the disaster. insider points of view for the future of critical care medicine," *American Journal of Respiratory and Critical Care Medicine*, vol. 192, no. 7, pp. 781–784, 2015.

[146] Fema P58, *Seismic performance assessment of buildings*, Methodology, Applied technology council (ATC), Redwood City, 2012.

[147] GG/T, *Evaluation Criteria for Seismic Toughness of Buildings*, China Standard Press, Beijing, China, 2020.

[148] D. Konstantinidis and N. Makris, "Experimental and analytical studies on the response of freestanding laboratory equipment to earthquake shaking," *Earthquake Engineering & Structural Dynamics*, vol. 38, no. 6, pp. 827–848, 2009.

[149] E. Costa, L. Di Sarno, G. Maddaloni, C. Petrone, and A. Prota, "Shake table tests for the seismic fragility evaluation of hospital rooms," *Earthquake Engineering & Structural Dynamics*, vol. 49, no. 2, pp. 1236–1255, 2014.

[150] K. C. Kuo, Y. Suzuki, S. Katsuragi, and G. C. Yao, "Shake table tests on clutter levels of typical medicine shelves and contents subjected to earthquakes," *Earthquake Engineering & Structural Dynamics*, vol. 40, no. 12, pp. 1367–1386, 2011.

[151] F. Nikfar and D. Konstantinidis, "Shake table investigation on the seismic performance of hospital equipment supported on wheels/casters," *Earthquake Engineering & Structural Dynamics*, vol. 46, no. 2, pp. 243–266, 2017.

[152] F. Nikfar and D. Konstantinidis, "Experimental study on the seismic response of equipment on wheels and casters in base-isolated," *Journal of Structural Engineering*, vol. 145, no. 3, pp. 243–266, 2019.

[153] F. Nikfar and D. Konstantinidis, "Evaluation of vision-based measurements for shake-table testing of nonstructural components," *Journal of Computing in Civil Engineering*, vol. 31, no. 2, 2017.

[154] J. W. Forrester, *Industrial Dynamics*, The MIT Press, Cambridge, MA, USA, 1961.

[155] J. C. Lowery, "Multi-Hospital validation of critical care simulation model," in *Proceedings of the simulation conference*, Ann Arbor, MI, USA, January 1993.

[156] J. R. Swisher, S. H. Jacobson, J. B. Jun, and O. J. C. Balci, "Modeling and analyzing a physician clinic environment using discrete-event (visual) simulation," *Computers & Operations Research*, vol. 28, no. 2, pp. 105–125, 2001.

[157] P. F. Yi, S. K. George, J. A. Paul, and L. Lin, "Hospital capacity planning for disaster emergency management," *Socio-Economic Planning Sciences*, vol. 44, no. 3, pp. 151–160, 2010.

[158] A. Basaglia, E. Spacone, J. W. van de Lindt, and T. D. Kirsch, "A discrete-event simulation model of hospital patient flow following major earthquakes," *International Journal of Disaster Risk Reduction*, vol. 71, Article ID 102825, 2022.

[159] B. Shahverdi, M. Tariverdi, and E. Miller-Hooks, "Assessing hospital system resilience to disaster events involving physical damage and Demand Surge," *Socio-Economic Planning Sciences*, vol. 70, Article ID 100729, 2020.

[160] A. Kaushal, Y. C. Zhao, Q. J. Peng et al., "Evaluation of fast track strategies using agent-based simulation modeling to reduce waiting time in a hospital emergency department," *Socio-Economic Planning Sciences*, vol. 50, pp. 18–31, 2015.

[161] M. Taboada, E. Cabrera, M. L. Iglesias, F. Epelde, and E. Luque, "An agent-based decision support system for hospitals emergency departments," *Procedia Computer Science*, vol. 4, pp. 1870–1879, 2011.

[162] R. Diaz, J. G. Behr, and M. Tulpule, "A system dynamics model for simulating ambulatory health care demands," *Simulation in Healthcare: The Journal of the Society for Simulation in Healthcare*, vol. 7, no. 4, pp. 243–250, 2012.

[163] L. Cassettari, R. Mosca, A. Orfeo, R. Revetria, F. Rolando, and J. B. Morrison, "A system dynamics study of an emergency department impact on the management of hospital's surgery activities," *International Conference on Simulation and Modeling Methodologies, Technologies and Applications*, vol. 111, 2013.

[164] G. B. Hirsch, "Modeling the consequences of major incidents for health care system," in *Proceedings of the 22nd International Conference of the System Dynamics Society*, pp. 25–29, Oxford, UK, January 2004.

[165] C. A. Arboleda, D. M. Abraham, and R. Lubitz, "Simulation as a tool to assess the vulnerability of the operation of a health care facility," *Journal of Performance of Constructed Facilities*, vol. 21, no. 4, pp. 302–312, 2007.