Bladder-Assisted Systole-Diastole Techniques: A Review

Zhaolin Wei

Abstract

Advancements in soft materials facilitate a progressive approach to medical treatments, crucial for individuals suffering from organ aging or irreversible damage. While much research focuses understandably on developing assistive technologies for primary organs such as the heart and lungs, the quality-of-life challenges associated with disabled secondary organs must not be overlooked. The living standards of numerous individuals have significantly declined due to disabled bladder. This Review article aims to provide researchers interested in implantable devices in the bladder with a comprehensive view of current devices. We identify the advantages and the remaining design challenges by evaluating various soft material-based approaches. Finally, promising directions for further development are discussed. It serves as a resource for any researcher invested in advancing this important but often overlooked area within the fields of soft robots and actuators.

1 Introduction

Urinary dysfunction is one of the common symptoms of autonomic neuropathy, which mainly manifests as difficulty in urination, urinary frequency, urinary retention, urinary incontinence, and automatic voiding. It is primarily caused by central or peripheral nerves involved in voiding or by bladder or urinary tract lesions. Among them, voiding dysfunction caused by neurological lesions is referred to as neurogenic bladder, which is the focus of applying bladder assistive devices [1].

Epidemiological data show that approximately 423 million people worldwide (over 20 years of age) suffer from some form of urinary incontinence [2]. Additionally, 70-84% of patients with spinal injuries experience neurogenic bladder dysfunction [3]. Patients with spina bifida also have a high prevalence of bladder dysfunction, with 60.9% of patients under the age of 5 years experiencing urinary incontinence [4]. Furthermore, brain tumours, diabetes mellitus, spinal cord injury, and vitamin B12 deficiency can also cause varying degrees of abnormality. Neurogenic bladder dysfunction may lead to complications such as renal failure, vesicoureteral reflux, urinary tract infections, and renal stones. The incidence of renal stones as a complication can be as high as 38%, and the incidence of bladder cancer in normal subjects is approximately 0.02%, but in patients with spinal injuries, this figure could range from 0.1% to 2.4% [5].

Clinically, the current treatment of neurogenic bladder mainly consists of conservative treatment, surgical treatment, and other therapies. Most of these treatments have been effective in alleviating symptoms and improving the quality of life for patients to some extent. However, they all have certain limitations and potential complications [6]. Clean intermittent catheterization is the most widely used method in clinical practice, with a 16-56% usage rate. It requires lifelong use. In surgical treatment, bowel bladder augmentation is considered the "gold standard" for bladder enlargement. It is widely used in treating patients who cannot tolerate conservative treatments. However, it increases the risk of urinary tract infection and urinary retention in patients. On the other hand, artificial urinary sphincter implantation has become the "gold standard" for the treatment of moderate-to-severe urinary incontinence and true urinary incontinence caused by sphincter dysfunction. Nevertheless, this procedure is associated with complications such as urinary tract infections, urethral atrophy, and urine retention. However, the detrusor muscle must be undamaged and still have intact connections to the brain. Various pharmacological treatments also have different tolerances and complications, etc. It is worth noting that no single approach can completely address the neurogenic bladder. Therefore, searching for advanced bladder assist devices may provide hope for patients suffering from the disease.

2 Overview of Methods for Assistive Devices

2.1 Manual Compression Device

In the early research on artificial bladder assist devices, the device had the following characteristics: the main body of the device was a urine storage bladder. The device's auxiliary power came from manual pressing by the person. The more typical device [7] as shown in **Figure 2.1.1**, consisted of a pressure pump manually pressed to generate a difference between internal and external air pressure, which would then discharge urine.

However, due to the lack of rational design in early devices and the inappropriate use of materials, patients implanted with manual compression devices often develop inflammation caused by incomplete urine drainage. At the same time, patients often experience increased pain during compression, which affects their quality of life. In addition, patients who have lost the ability to urinate cannot rely on their senses to urinate normally due to the lack of a control valve.

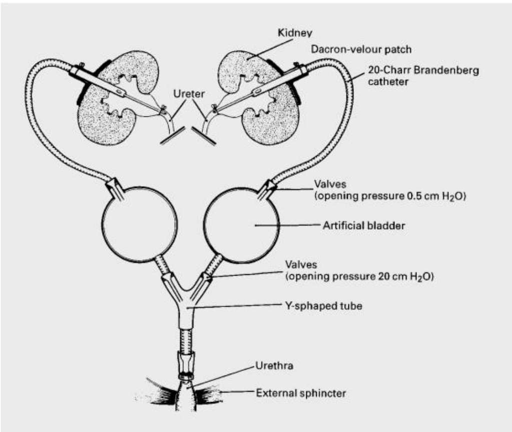

Figure 2.1.1 Expansible-contractile bladder prosthesis: the Aachen model

2.2 Mechanical Structure-Driven Device

2.2.1 Extracorporeal Electromagnetic Bladder Power Pump

A power pump model was proposed by a scholar in China [8], which is mainly composed of three parts: an electromagnet, a stator, and an actuator. The stator is made of non-magnetic material fixed to the pelvic bone. The stator is made of non-magnetic material and fixed on the pubic bone. The actuator uses rubber to enclose several permanent magnetic sheets, which form a working capacity cavity with the stator.

During the urine storage phase, the electromagnet does not generate a magnetic field; the actuator is relaxed. Thus, the bladder is not compressed. As urine accumulates, the bladder expands, driving the actuator to rise. When the stored volume reaches the level of urination, the electromagnet is activated. Under the influence of the magnetic field, it will attract the permanent magnetic sheet in the actuator, which presses the bladder to contract and discharge the urine. When urination is complete, the electromagnet stops working, and the actuator returns relaxed.

2.3 SMA Assistive Device

2.3.1 SMA Spring-Assisted Device

With the development of shape memory alloy technology, the material has been proven to have good biocompatibility in recent years and is now extensively utilized in various types of control devices. In 2007, Kazuo Kiguchi of Japan proposed an assisted voiding device [9] as shown in **Figure 2.3.1.** The device used a spring fabricated using the thermal denaturation of SMA, and a Peltier Element was used to detect changes in bladder temperature and provide a tensile force. The advantages of this device are its simple structure and reliability.

The drawback, however, is that the device requires a 6V, 6A power supply in an analogue environment to provide it with voltage. The maximum current allowed to pass through the human body is 0.01A, which is significantly low. The insulation of the device is a major limiting factor. On the other hand, the spring-loaded pull structure results in only one direction of force being provided during bladder compression.

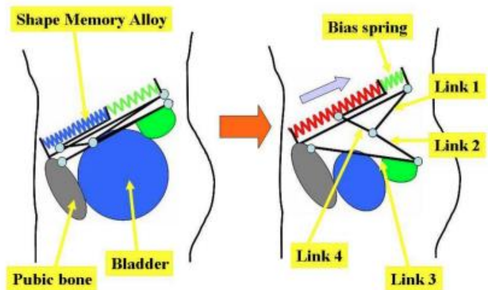

Figure 2.3.1 SMA thermal responsive spring-assisted device

However, there is still room for improvement in terms of control accuracy and comfort.

2.3.2 Encapsulated SMA

The development of 3D printing technology has allowed more variations of shape memory metals. Faezeh Arab Hassani et al. proposed a urinary voiding device based on 3D printing technology and SMA [10].

The device is designed to attach the shape memory metal to the bladder in a loop shape, providing a better fit compared to spring-loaded assistive devices. Therefore, it also applies force more evenly and provides more precise control.

On the other hand, the device still employs the thermal denaturation of SMA, which may lead to heat breakage of the wires during use, potentially creating a hazardous situation and reducing the service life. In addition, in the experiment, the device was found to discharge 8% of urine in one voltage cycle, meaning that several cycles were required to achieve an ideal amount of urine discharge. Several 8-second cycles of voltage signals were required to activate the device in the experiment to achieve a higher urination efficiency, which would put more psychological pressure on the patient.

2.4 Soft Bladder Assistive Device

2.4.1 Soft Sensor Bladder Assistive System

Faezeh Arab Hassani and colleagues proposed another assistive device for the bladder utilizing soft sensors and shape memory alloy [11]. The device consists of two PVC plates, each equipped with a layer of soft sensors, clamping the bladder in the center as shown in **Figure 2.4.1.** The soft sensors are capable of converting changes in bladder volume into changes in capacitance, transmitting signals to the actuator when the bladder is filled.

However, shape memory alloy is still used as the driving mechanism in the device. Upon receiving the signal, the actuator heats the shape memory alloy, causing the spring to contract, thereby bending and exerting pressure on the bladder through the PVC plates, resulting in successful urination.

Due to the use of soft sensors and a novel structure incorporating shape memory alloy, this device's efficiency is significantly enhanced, achieving a urination efficiency ranging from 71% to 100%. Moreover, the device is capable of completing the assisted urination process within one to two cycles, greatly reducing the time required.

However, the device requires an increase in the thickness of the encapsulation layer to minimize the impact of fluid corrosion, which results in increased stiffness and decreased sensitivity of the sensors. The design of the encapsulation layer thickness still needs to be tested in live animal experiments.

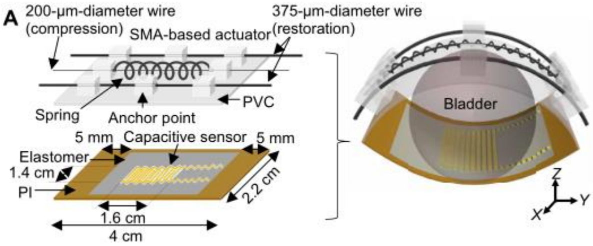

Figure 2.4.1 The schematic of the integrated capacitive sensor with the SMA-based actuator.

2.4.2 Thermal-Responsive Hydrogel

Water gel is a network of hydrophilic polymer chains with water as the dispersed medium. In recent years, Lonow et al. have innovatively discovered that multi-step folding of stimulus-responsive polymer bilayers can be used to create complex 3D structures [13]. The most used material for this purpose is a combination of an active layer and a passive layer made of poly (N-isopropyl acrylamide) (PNIPAm) [12]. The properties of the hydrogel depend on the selected polymer and can expand or contract under external stimuli.

Yang Xuxu et al. utilized the expandable and contractible properties of hydrogels to develop a composite structure that can directly adhere to the surface of the bladder as an artificial detrusor muscle for bladder contraction. The device comprises non-responsive rigid hydrogel, thermal-responsive hydrogel, silk scaffold, and flexible electronic components. The artificial detrusor muscle has a "cap-like" shape with a circular hole in the middle and is sutured onto the bladder using surgical threads.

The device utilizes flexible electronic components to convert changes in bladder volume into signals for heating by the heater. When the thermal-responsive hydrogel reaches the preset temperature, the gel expels water and contracts, exerting pressure on the bladder for voiding. In experiments, the device achieved satisfactory results, as the TRH membrane contracted when the temperature exceeded 35°C and returned to its initial state after approximately 30 minutes following the heating process. The device operates effectively at this temperature without affecting the surrounding tissues, organs, and muscles.

2.4.3 Soft Magnetic Robotics

The use of magnetic soft-bodied robots for the task of drug delivery is a viable option[14]. A Huazhong University of Science and Technology team has proposed a new way of squeezing the bladder with an implantable magnetically controlled soft body robot[15]. Magnetically controlled soft robots are often used to work inside the human body by remote control, thanks to the penetration and safety of magnetic fields. The magnetic field, in turn, combines the ability to deliver high output to meet the movement demands of the bladder, a non-rhythmic active motor organ.

According to the functional design, the Magnetic Robotic Bladder (MRB) needs to work inside the body for a long period, which requires excellent compatibility and stability of the MRB material. The authors designed a large-area multilayer coating approach for magnetically responsive soft materials, using silica gel as a transition layer to cover a biocompatible hydrogel film on the surface of the complex and rugged magnetically responsive soft materials, which effectively reduces the friction as well as the biotoxicity on the surface of the MRB so that the MRB can be implanted safely in vivo. At the same time, a mesh material is embedded in the part of MRB that generates large deformation during movement, which enhances and toughens the silicone matrix material so that the MRB can complete many repeated extrusions.

The MRB approach bypasses the common neuromodulation route for organ function reconstruction and uses a novel soft robot to directly simulate organ muscle movement to restore the physiological function of bladder voiding, providing a new therapeutic opportunity for UAB patients.

3 Future Perspectives and Conclusion

This article investigates artificial bladder assistive devices in the context of a large base of patients with neurogenic bladder and certain deficiencies and complications in clinical treatments. A variety of materials have been put into practice, which can be stimulated by electricity, magnetics, hydraulics, or temperature. Each of these assistive devices showed advantages and disadvantages in addition to being promising for a specific range of applications, as summarized in **Table 1**.

The forefront research in artificial bladder assistive devices has achieved diversified development. However, existing artificial bladder assistive devices still face numerous challenges in practical applications, such as poor device comfort, inadequate control precision to meet practical requirements, and difficulties in long-term operation inside patients' bodies. Traditional methods use accurate control to exert forces on the wall of the bladder. Nowadays, soft actuators are challenging traditional strategies in implantable devices.

Magnetic stimulation is regarded as promising due to its easiness in accurately controlled magnitude and direction. Magnetic fields have good penetrating properties, and the magnetic field easily passes through the body's skin to reach the organs. In the presence of a magnetic field, the implantable bladder assist device can be turned on or off to assist. Meanwhile, magnetic particles coupled with conducting polymers may enable wireless powering and stimulate pacemaker-like implant circuits. Changes in magnetic flux induce electrical currents, triggering bladder wall contractions on demand from outside the body.

A new artificial bladder assist device is proposed based on magnet-soft materials' good magnetic and mechanical properties. Based on this, a preparation scheme for a magnetic bladder power pump is proposed, in which hard magnetic particles are embedded in a composite elastomer matrix. Then, its internal space magnetization profile is regulated by a direct magnetization strategy of pulsed strong magnetic field focusing, and a feasibility verification analysis is completed in combination with a driving magnetic field system. In turn, the feasibility of further research on this artificial bladder assist device was verified.

Hydrogel is considered a less repulsive soft material, and if researchers combine hydrogel with magnetic materials, they could use it as a better implantable bladder assistive device with a wide range of applications. Novel magnetic hydrogels also open opportunities. When exposed to an alternating magnetic field, these smart biomaterials undergo sol-gel transitions, transforming between swollen and contracted states[16]. Biodegradable magnetic hydrogel grafts or fillers could one day non-invasively augment native bladder capacity and compliance. Further fine-tuning composition and microstructure will increase responsiveness to optimize therapeutic effects.

Finally, many of the projects were experimented with under only one driving factor, and future testing is needed for bladder contraction performance under different conditions, testing targets such as flow rate, morphology, and other performance parameters for widely practical applications of bladder assist devices.

Table 1. Comparison between the performances of the different types of assistive devices discussed in this review article.

Type of assistive device		Advantages	Limitations/Challenges
Manual compression device		Low cost	Large displacement
Mechanical structure-driven device	Extracorporeal Electromagnetic Bladder Power Pump	Quick response Highly Stability High actuating force	Rigid and bulky Limited flexibility and scalability of the full system
SMA Assistive Device	SMA Spring-Assisted Device	High energy density Low cost Stores and recovers kinetic energy	Limited flexibility Challenges in precise control High current
	Encapsulated SMA	Sensitive to temperature change	Hysteresis Risky Short service life

Soft Bladder Assistive Device	Soft Sensor Bladder Assistive System	Quick response Efficient	Poor stability
	Thermal-Responsive Hydrogel	Biodegradable Low density High stretchability Scalable	Low modulus, low stiffness Long recovery time
	Soft Magnetic Robotics	Linear effect Highly precise output	Complex manufacturing process

Reference

[1] 贾建平. 神经病学(第 8 版)[M]. 人民卫生出版社, 2018.

[2] Tran LN, Puckett Y. Urinary Incontinence. 2022 Jan 2. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2022 Jan–. PMID: 32644521.

[3] 周慧宇,邓欣,双卫兵.脊髓损伤后神经源性膀胱治疗的研究进展[J].泌尿外科杂志(电子版),2020,12(03):6-12.

[4] Tayyeb M, Tadi P. Neurogenic Bladder. 2021 Sep 29. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2022 Jan–. PMID: 32809452.

[5] BrigitteSchurch,CécileTawadros,StefanoCarda.Dysfunction of lower urinary tract in patients with spinal cord injury.2015 May 21.Handbook of Clinical Neurology. 130: 247-267. PMID:26003248

[6] 陈树,张天禹.神经源性膀胱的分类及治疗进展[J].世界最新医学信息文摘,2018,18(58):84-86.DOI:10.19613/j.cnki.1671-3141.2018.58.037

[7] D. Rohrmann et al, "Alloplastic replacement of the urinary bladder," The Journal of Urology, vol. 156, (6), pp. 2094-2097, 1996.

[8] 李笑，关婷. 一种体外电磁驱动的膀胱动力泵: ZL200710031081. 1 [P]. 2010－12－15

[9] K. Kiguchi et al, "Development of a urination assist system - A bladder compressing system with a link-work mechanism," in 2007, . DOI: 10.1109/ICMECH.2007.4280068.

[10] F. A. Hassani et al, "A 3D Printed Implantable Device for Voiding the Bladder Using Shape Memory Alloy (SMA) Actuators," Advanced Science, vol. 4, (11), pp. 1700143-n/a, 2017.

[11] F. Arab Hassani et al, "Soft sensors for a sensing-actuation system with high bladder voiding efficiency," Science Advances, vol. 6, (18), pp. eaba0412-eaba0412, 2020.

[12] R. Kempaiah and Z. Nie, "From nature to synthetic systems: shape transformation in soft materials," Journal of Materials Chemistry. B, Materials for Biology and Medicine, vol. 2, (17), pp. 2357-2368, 2014.

[13] Chen W, Chen X, Yang M, et al. Triple-configurational magnetic robot for targeted drug delivery and sustained release[J]. ACS Applied Materials & Interfaces, 2021, 13(38): 45315-45324.

[14] Chen W, Chen X, Yang M, et al. Triple-configurational magnetic robot for targeted drug delivery and sustained release[J]. ACS Applied Materials & Interfaces, 2021, 13(38): 45315-45324.

[15] Youzhou Yang et al., Magnetic soft robotic bladder for assisted urination.Sci. Adv.8,eabq1456(2022).DOI:10.1126/sciadv.abq1456

[16] Xue, Y., & Sun, L. (2022). Magnetic hydrogels with ordered structure for biomedical applications. Frontiers in Chemistry. https://doi.org/ 10.3389/fchem.2022.1040492