

The Potential of Electrical Stimulation and Smart Textiles for Patients with Diabetes Mellitus



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ABSTRACT

Diabetes mellitus is one of the most frequent diseases in the general population. Electrical stimulation is a treatment modality based on the transmission of electrical pulses into the body that has been widely used for improving wound healing and for managing acute and chronic pain. Here, we discuss recent advancements in electroceuticals and haptic/smart devices for quality of life and present in which patients and how electrical stimulation may prove to be useful for the treatment of diabetes-related complications.

Introduction

Due to the endemic extent type-2-diabetes and the metabolic syndrome is one of the major challenges and burdens to our health systems, requiring the development of novel preventive and therapeutic approaches for the treatment of the disease and the associated complications. Currently, a revolutionary development is going on in the field of so-called electroceuticals. These are medi-

cal devices used for the treatment of specific pathological conditions and diseases with the use of electrical impulses. Although the best known example is the cardiac pacemaker, impressive progress has also been made in the treatment of other diseases. For example, so-called brain pacemakers for deep-brain-stimulation have been established as a promising alternative or add-on therapy for neurological disorders or pathological conditions that were other-

wise unresponsive to conventional treatment measures (e. g., Parkinson's disease, epilepsy, obsessive-compulsive disorder) [1–3]. Furthermore, based on gastric electrical stimulation, several devices (“gastric pacemakers”) have been successfully introduced into the treatment of obesity and type-2 diabetes, thereby targeting the metabolic syndrome as another area for the potential therapeutic application of electroceuticals [4–6]. However, in addition to the use of implantable devices that require a surgical procedure, the consideration of non-invasive electroceutical gadgets appears reasonable in particular situations in patients with diabetes mellitus. For example, many patients with diabetes suffer from neuropathy or angiopathy in particular of the lower limbs or the diabetic foot syndrome. These conditions may potentially benefit from transcutaneous electrical nerve stimulation [7–12]. In addition, many patients exhibit sensory impairments that promote the development of foot ulceration and negatively affect balance control and gait (Peters, 2016; Ziegler, 2022). and based on this background the development of practical electronic textiles meeting criteria of everyday life requirements is becoming an indispensable prerequisite for a successful therapy [13].

Advancement in electroceuticals and haptic/smart devices for quality of life

The potential impact of electroceuticals on quality of life is well established and strikingly illustrated by the cardiac pacemaker [14]. However, this development dates back into the fifties of the last century and since then, basic and applied sciences have shown rapid progress in almost all areas. Combining both – advances in electronics and material sciences – has made further improvements as well as the engineering of novel electroceutical devices possible.

In particular, different types of electrical stimulation, defined as the non-invasive transmission of electric signals into the body, have been developed. The neuromuscular electrical stimulation (NMES) is characterized by electrical impulses that are delivered to the muscle through electrodes placed on the skin that subsequently lead to muscle contraction [15]. NMES has been used for the treatment of muscle weakness by patients with prolonged hospitalization [16], in cancer rehabilitation [17], in prevention of thromboembolism [18], for motor recovery in children with neurologic conditions [19] and for the treatment of sports injuries [20]. Similarly, peripheral electrical stimulation (PES) applied through electrodes have been used for the recovery from injuries, for the treatment of chronic pain and for promoting motor rehabilitation [21, 22]. Transcutaneous electrical nerve stimulation (TENS), which runs at one mA have been also tested primarily as treatments of pain [23–25], but may also improve sensomotoric impairments that are evident in terms of vibration perception, balance control and gait [23, 24]. In addition, microcurrent electrical nerve stimulation (MENS), which runs at one μ A below the sensation threshold may also exert beneficial effects in muscle function and growth [25, 26]. Stochastic Resonance, similar to MENS, works below the sensation threshold. It has been shown that subthreshold electrical (white or pink) noise can improve the perception of tactile and vibratory stimuli, balance and gait behavior [27–30]. However, little research has been done on the potential of this form of electrical stimulation in patients with diabetes mellitus [28]. Additionally, electrical stimulation can be used as adjunctive therapy in patients undergoing

plastic surgery in order to ameliorate graft survival, to reduce necrosis after foot reconstruction and to improve postoperative recovery [31].

Regarding the material aspects extremely high standards and requirements concerning safety, mechanical stability, durability, sustainability as well as patient comfort must be met. Furthermore, in the case of external haptic devices or electronic textiles, also optical or even fashionable aspects have to be taken into consideration in order to ensure patient acceptance. Although all these aspects are posing a huge challenge to very different disciplines (medical researchers, engineers, material scientists, textile engineers, designers, craftspeople), the joint efforts of all involved parties also offer huge opportunities for a novel and rapidly growing industrial branch serving patient's needs and improving their lives.

Why Diabetes?

Diabetes mellitus is one of the most prevalent diseases worldwide with an increasing incidence. Currently, the prevalence of diabetes mellitus in Germany is about 8%. This is mainly due to the life-style-associated increasing prevalence of obesity as well as the current demographic development with more people reaching advanced age. The major problem with diabetes mellitus is the frequent development of complications such as diabetic nephropathy, retinopathy, micro- and macroangiopathy, neuropathy – alone or in combination – with severe and potentially disabling consequences [32]. For example, patients with the diabetic foot syndrome, which is based on the disastrous combination of neuropathy, angiopathy and sometimes also osteoarthropathy as worst-case-scenario, frequently suffer from poor healing foot ulcers resulting in motoric instability, immobility and frailty [33]. Diabetic neuropathy affects 20–35% of patients with diabetes [34] and it is subdivided into sensory, motor and autonomic peripheral neuropathy [33]. People with diabetic peripheral neuropathy experience a reduction of vibration sense and of superficial sensitivity [35, 36]. Additionally, often they suffer from paraesthesia, that in certain cases it may also be painful or become stressful (e. g., by restless-legs syndrome). Diabetic neuropathy of the lower limb and the diabetic foot syndrome are both difficult to treat. There are numerous reports on beneficial effects of electrical stimulation in diabetes mellitus and in particular effects of neuromuscular stimulation have been studied in diabetes. Similarly, electrical stimulation has been also tested for the treatment of gastroparesis, which is also often observed in patients with diabetes due to neuropathy [37]. Gastric electrical stimulation facilitates gastric emptying by affecting sensory transduction to the brain and it has been approved by the Food and Drug Administration (FDA) for the treatment of vomiting and nausea in patients with diabetic or idiopathic gastroparesis [37]. Additionally, gastric electrical stimulatory devices (GES) have been developed and successfully tested in clinical trials for the treatment of obesity and in some cases of type 2 diabetes and metabolic diseases [38]. Recent reports indicate also some other unexpected effects of nerve stimulation. For example, Guyot et al. (2019) [39] described that pancreatic nerve stimulation inhibits the onset of autoimmune diabetes in mice and Luo et al. (2021) [40] presented evidence from a mouse model that non-invasive microcurrent electrical nerve stimulation may improve glycaemic control comparable to pharmacologic anti-diabetic com-

pounds. Taken together, there are promising data indicate that electroceuticals may be helpful in the treatment of diabetes and associated problems.

The geriatric patient with diabetes and new electric materials

Type-2-diabetes is associated with increasing age and age-related problems make the diabetic patient even more fragile and susceptible to severe complications. For example, decreasing kidney function in the elderly may be even more diminished by diabetic nephropathy or glycemic control may be further impaired due to age related sarcopenia or frailty. The latter condition – frailty syndrome – is of particular importance because it may dramatically deteriorate prognosis in patients with diabetes. In order to prevent or reduce muscle weakness in patients with diabetes, numerous studies on neuromuscular electrical stimulation (NMES) have been performed. For example, Takino et al. (2022) [41] reported data suggesting that a short course of NMES may mitigate muscle weakness and functional impairment in patients with after surgery. In addition, electrical muscle stimulation may be useful for preventive purposes as supportive measure to improve exercise and strength training and make it more efficient in the elderly [42]. Also, flexible electrical strain sensors may be used to monitor physical performance and enhance motivation and wearable devices have been developed for this purpose [43].

Diabetic foot and electrostimulation

The diabetic foot syndrome is one of the most disabling complications and associated with a serious prognostic deterioration for patients with diabetes mellitus. This is even worse when amputations cannot be avoided. In order to prevent amputations, numerous treatment regimens have been established in order to improve limb perfusion, wound healing and outcome.

The effects of electrical stimulation on blood flow and capillary architecture have been studied over more than three decades and data from diabetic animal models showed encouraging results [44]. Specifically, electrical stimulation may be beneficial for diabetic foot through multiple mechanisms. First, it may improve wound healing by increasing blood flow through enhancement of capillary density by increased angiogenesis [45, 46]. Second, it may improve the migration of macrophages, fibroblasts and endothelial cells in the wound, thus facilitating the healing process of the wound, which is often impaired in patients with diabetes [9]. Third, although still debated, it may attenuate bacterial proliferation and disrupt bacterial membrane, thus reducing infection [9].

In clinical practice, different therapeutic regimens based on electrical stimulation have been used. The efficacy of those procedures on the healing process of diabetes related ulcers has been reviewed and a systematic meta-analysis has been published recently [7]. In comparison to placebo and standard treatment, patients with diabetes related ulcers had a significant benefit from electrical stimulation regarding ulcer reduction and healing rates. Based on this, efforts to further improve and optimize the results of electrical stimulation are in progress and promising results on the effectiveness of combination of electrical stimulation with other non-invasive measures (e. g., ultrasound) have been published [47].

Also, wearable flexible devices facilitating electrostimulation for the healing of foot wounds are at different stages of development and even home-based systems as a supportive therapy to speed up the healing process have been tested [48, 49]. Furthermore, electrostimulatory systems to improve mobilization and walking abilities of patients with diabetes following minor amputations have been tested and shown encouraging results [50].

In summary, electrical stimulation and smart textiles based on this principle promise a great potential for the supportive treatment of patients with diabetes mellitus and associated complications like the diabetic foot syndrome.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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